ELECTROPALATOGRAPHY IN THE INVESTIGATION OF SOME PHYSIOLOGICAL ASPECTS OF SPEECH PRODUCTION.

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ABSTRACT

Chapter 1 : The primary aim of most experimental phonetic research today is to obtain evidence of neural programming and control functions from close observation of the peripheral output of speech production. Interest is focussed particularly on the dynamics of articulatory structures especially complex organs such as the tongue. Detailed investigations in this field have been facilitated by a wide range of recent instrumental techniques, such as electropalatography, which provides quantitative and qualitative data on the exact location and timing of tongue contacts with the palate during continuous speech.

Chapter 2 : Before undertaking investigations into the dynamics of articulation we need an adequately rigorous anatomical and physiological framework. The framework outlined here includes sections on the peripheral nervous system, biomechanical constraints on lingual articulation and detailed myology of the tongue.

Chapter 3 : As a background to the development of the Edinburgh system of electropalatography, various instrumental techniques for investigating lingual activity during speech are reviewed. The particular difficulties associated with investigations of the tongue and the attempts of some instrumental techniques to overcome these difficulties are discussed.

Chapter 4 : The Edinburgh system of electropalatography is described in detail and compared with other similar techniques.

Chapter 5 : As a starting point towards a comprehensive phonetic theory of linguistic performance, the results of instrumental investigations on the tongue are combined with the anatomical and physiological framework in Chapter 2, in proposing a parametric approach to lingual articulation, where an attempt is made to specify all known lingual motions and configurations in terms of seven articulatory parameters and their hypothesized underlying physiological mechanisms. Some basic concepts of phonetic theory are rescrutinized in the light of this parametric approach.

Chapter 6 : An investigation into some aspects of the sensori-motor control of speech,particularly of complex articulations such as [s] and [ʃ] was carried out. The experiment involved altering different types of sensory feedback by topical and lingual block anaesthesia and auditory masking procedures and examining the effect on various articulatory and acoustic aspects of speech production. Electropalatography was used to

provide quantitative data concerning changing tongue configurations during articulation of the test fricatives. The results showed considerable "overshooting" of target articulation occurring during the anaesthetic and masking conditions, and an explanation for this was sought in terms of a neurophysiological "priming in advance" hypothesis.

Chapter 7 : From the results of the experiment described in Chapter 6 a feedback theory of the myodynamic control of speech production is proposed.

CONTENTS

CHAPTER 1

INTRODUCTION : GENERAL HISTORICAL BACKGROUND AND AIMS OF THE THESIS.

Throughout the history of science, there has always been a close relationship between the development of a theory and the availability of relevant instrumental technology. Theoretical speculation has often encouraged the development of suitable instrumentation to allow particular hypotheses to be tested. This was particularly true, for instance, of the early research on the nature and properties of electricity by scientists such as Faraday, Ampère, Volta etc., who often found it necessary to construct special apparatus in order to demonstrate their theories. However, the relationship between theory and instrumentation is not entirely a one-way relationship. The availability of particular types of instruments can act as a predisposing factor, encouraging theoretical interests to expand in one direction rather than in another. This seems to be the case with the history of experimental phonetics, where the influence of technology on theoretical developments is clearly evident.

In the early part of this century, experimental phonetic research was characterized by a great deal of interest in articulatory aspects of speech production rather than in the acoustic nature of sound transmission through the air. This was due, not so much to phoneticians not being interested in acoustics, but to the relative lack of suitable instrumentation for making detailed investigations of acoustic data. It was possible to investigate certain aspects of the wave-form by means of Fourier analysis, but the collation of data and the actual mathematical calculations involved made this an extremely complex and time-consuming process. There were, however, a number of instrumental techniques available for investigating articulatory activities. These included such techniques as palatography, kymography, radiography etc. Radiography at the time seemed a particularly promising means of investigating articulatory activities in the oral tract. Previous to the invention of x-rays, the only way to investigate the more inaccessible articulatory structures such as the soft palate, back part of the tongue and pharynx was either to insert various types of probes into the mouth cavity, or infer the activities of these structures from air-flow data recorded by a kymograph. Radiography seemed a promising method for obtaining information such as the position of the tongue in relation to the palate, the degree of opening of the soft palate, width of the pharynx etc. Consequently, a great deal of research was carried out making use of static sagittal x-ray photographs (see later, Chapter 3). In these static radiographic investigations, the usual procedure was to have the subject articulate a prolonged vowel sound, maintaining his articulatory structures for a second or two, while the x-ray photograph was taken. Using this sort of technique, phoneticians described the vowel sounds of many different languages. Although useful, the x-ray techniques proved to be rather limited. Because of the radiation danger, only a small number of vowels could be analysed. Incidentally, it seems that some of the early investigators did not realize the potential danger of x-rays. Russell (1928) reports a few cases where the experiments had to be abandoned because the subjects suffered severe radiation burns. Palatography, both direct and indirect, (see Chapter 3 later) was used extensively by early experimental phoneticians for examining the location of the tongue contact with the palate during the articulation of single isolated sounds.

Use of techniques such as static radiography and palatography probably influenced to some extent the theoretical standpoint held by some early phoneticians that speech production consisted of a series of static, momentary postures linked together in a linear sequence. (Abercrombie, 1965 : 121, calls this the "posture-and-glide" approach). Recent investigations have shown however, that speech is very much a "dynamic process, involving many co-ordinated articulatory processes, rather than a sequence of relatively static postures involving only one or two of the articulatory organs" (Henderson, 1965 : 16). The dynamic nature of articulation is seen later in Chapter 6, where tongue movement during the release phase of fricatives is demonstrated. Thus in one sense it seems that the theoretical interests of early investigators were influenced by instrumental technology.

During these early years of experimental phonetics, some attempts were made to describe the physiological mechanisms that underline speech articulations. A number of ingenious instruments were developed to measure muscular contractions. Scripture (1902 : 335) for instance, describes a "geniohyoid tambour" (see later Chapter 3, section 1. 1. 2. (e)), which was designed to respond to movement of the geniohyoideus muscle. He postulated a direct relationship between contraction of the geniohyoideus muscle and elevation of the tongue, and drew diagrams purporting to show tongue movement during the articulation of specific sounds. However, knowledge of the anatomy and physiology of the tongue muscles suggests that there is not necessarily a one-to-one correspondence between contraction of the suprahyoid muscles and tongue elevation. (see later, Chapter 2). Experiments such as Scripture's indicate that the traditional approach perhaps tended to overemphasize the importance of specific muscles in characterizing the articulatory movements of complex organs such as the tongue.

Interest in the dynamics of speech increased during the 1930's, when a new school of phonetics emerged, challenging the traditional idea of speech as consisting of a succession of discrete "building-blocks" or phonemes, arranged in a linear sequence. J. R. Firth and his followers adopted a more dynamic view of speech as being the output of a number of overlapping and interlocking acoustic and articulatory parameters, which were called prosodies. Some of the traditional instrumental techniques such as palatography were still used by these phoneticians, but they were used for slightly different purposes. Whereas the early phoneticians made palatograms primarily to illustrate areas of tongue-palate contacts for specific isolated segments, Firth produced <u>word palatograms</u> (Firth, 1948a) which were composite representations of the contact area for a sequence of segments. By means of word-palatograms, Firth could illustrate certain prosodic features such as palatalization, which characterized a succession of sounds. Thus we see instruments used here to provide data supporting the parametric approach to theory in which speech production is regarded as characterized by a number of parameters or variables, continually present but changing in value.

In the 1940's, the sound spectrograph was developed (Koenig, Dunn and Lacy, 1946; Potter, Kopp and Green, 1947), and this machine provided for the first time a relatively economic and rapid means for investigating the acoustics of speech. Phoneticians no longer had to resort to complex methods of analysing the wave-form. It is not surprising therefore,that for twenty years after the invention of the sound spectrograph, research interests were centred on the acoustic parameters of speech, rather than on other areas of speech production. The value of this research lay particularly in the emphasis it placed on the dynamics of the acoustic nature of speech production, but also on the underlying articulatory activities. Interest in investigating the relative importance of certain acoustic cues for the perception of speech encouraged the development of acoustic speech synthesizers such as Edinburgh University's Parametric Artificial Talker in the 1950's, (Lawrence, 1953). The importance of synthesizers such as P. A. T. to research, lay in the fact that it was possible to alter experimentally some of the acoustic parameters such as intensity, fundamental frequency, formant frequency, etc., and assess the effect of such alterations on perception by playing the result to a panel of listeners. Typical of the sort of research using synthesizers such as P. A. T. were investigations into the relative importance for perception of different acoustic correlates of stress, such as intensity, fundamental frequency, duration, (e.g. Fry, 1958).

Although the primary interest of many investigators at this time was focussed on the acoustic aspects of speech production, as mentioned above, some effort was made to speculate on the articulatory parameters underlying the acoustic output. Thus Fant (1962) and Stevens and House (1955) among others, outlined mathematical formulae by which articulatory factors such as position of narrowest constriction in the oral tract, the area of constriction, etc. could be specified from knowledge of the formant frequency levels. The relationship is, however, extremely complex (see later Chapter 3, section 1.2.1.).

During the last few years interest seems to have swung back once again to articulatory aspects of speech production. As Lehiste (1967 : vi) says, "The time appears to be right for a stocktaking in the field of acoustic phonetics. We seem to have reached a plateau and the focus of research in experimental phonetics seems to have shifted, perhaps temporarily, to areas about which less is presently known. There is a renewed interest in articulatory phonetics. . . ." This trend has been encouraged partly by the current availability of a wide range of instrumental techniques directed at the study of articulatory parameters and their underlying physiological mechanisms. Modern electronics has made available to us many sophisticated devices which are gradually replacing older techniques such as registration of air-flow data by means of the drum kymograph. With the aid of such technology, the phonetician is able now to study for the first time, microscopic details of the timing and sequence of articulatory movements, which previously, because of their speed and complexity, resisted successful investigation, (see later Chapter 3).

One of the most important areas of interest has been the upper oral tract, particularly the tongue. For many years information concerning the dynamics of lingual articulation was somewhat limited owing to the unique difficulties associated with investigating that organ (see Chapter 3, Introduction). Now, however, techniques such as electromyography and cinefluorography have provided valuable data on different aspects of lingual articulation, although there are many disadvantages associated with their use. Another of the potentially promising techniques to emerge in recent years has been electro-palatography, which provides, for the first time, quantitative data concerning the exact location and timing of tongue contacts with the palate during continuous speech. In the present research, one of the principal aims has been to develop electropalatography as a research technique and explore its application in providing quantitative experimental data on lingual activity. The development of the Edinburgh system of electropalatography and its particular advantages in providing data which is unobtainable by other experimental techniques for investigating lingual articulation, are discussed in Chapters 3 and 4 of this thesis.

With the aid of experimental techniques such as electromyography, cinefluorography and electropalatography, phoneticians now are attempting to improve the descriptive procedures of phonetic theory.

There is strong indication now that many of the traditional concepts of theory need to be rescrutinized in the light of recent experimental results. One of the underlying aims of this thesis is to point to how descriptive procedures might be improved by means of a parametric approach to articulation. The main focus of attention will be lingual activity, particularly during the articulation of fricatives such as [s], [ʃ] etc. As a starting point towards a comprehensive phonetic theory of speech performance, a set of articulatory parameters specifying tongue positions and configurations, by means of which the lingual articulation of any sound can be accurately described,is suggested in Chapter 5 of this thesis. In addition to the formulation of the set of articulatory parameters, an attempt has been made to describe the physiological mechanisms underlying these parameters. Before we speculate on physiological mechanisms, however, we need a comprehensive anatomical and physiological framework of the tongue. Chapter 2, section 3, provides such a framework.

The importance of this sort of parametric approach to descriptive theory emphasized in this thesis, lies partly in its implications for a universal phonetic theory. It is suggested for instance in Chapter 5, that it may be possible to describe all sounds in a cline from "simple" to "complex" with reference to the articulatory parameters and underlying physiology. Complex sounds would be associated with maximum interaction of the articulatory parameters and most delicate and precisely co-ordinated muscular systems. These sounds,which would presumably include "grooved" fricatives such as [s], [ʃ] and affricates [tʃ], [ts] etc. seem to have certain universal characteristics; they are usually correctly articulated later in a child's acquisition of speech than less complex sounds such as [p], [b], [m]; they cause most difficulty to patients suffering from sensori-motor co-ordination impairments in the oral region; and they seem more likely to interact in tongue slips, particularly as regards place of articulation (see Boomer and Laver, 1968). In addition, because of the hypothesized greater delicacy of tactile sensory discrimination in the front part of the tongue than in the back part, one would expect that if complex articulations occur in a language,they are more likely to occur in the front part of the oral region than in the back. (see Hardcastle, 1970, and Chapter 5).

The general aim to improve descriptive procedures used in phonetics has meant more interest is being shown in the minute details of speech production particularly in the timing and co-ordination of the articulatory structures. This interest has led phoneticians into speculation about how the complexities of articulations are controlled by the brain. As Laver (1970 : 60) says, "Until very recently, phonetics has largely limited its interest in speech production to the study of articulation; it is now in the process of expanding its theoretical apparatus to include the study of neurolinguistic programming." Because of the inaccessibility of the live human brain to direct investigation,we must infer neural activity from a detailed study of the peripheral end of the speech chain, the contraction of muscles, movements of the articulatory organs and the resulting acoustic output. It is investigation of some aspects of the peripheral end of the speech chain and the light it can throw on neural control mechanisms that is the principal aim of this thesis.

Before we can speculate on speech articulation and its neural control, however, we must be fully aware of the available resources the body has at its disposal for making any sort of control possible. One of the main limitations of early work on aspects of neuromuscular control by both phoneticians and physiologists was that they often formulated far too simplist models of performance,because they were simply not aware of the full potential of the body's muscular and sensory resources. Now with the help of recent electrophysiological and histological techniques, anatomists and physiologists are in a better position to offer us more comprehensive descriptions of the body's resources for neuromuscular control. Most of this research has been relatively inaccessible to phoneticians, so one of the objects of this thesis is to attempt a synthesis of most of the relevant research carried out on the oral mucosa and the lingual musculature,and to present it concisely, with consideration of phonetic relevance firmly in mind. (This outline constitutes the greater part of Chapter 2). We will then hopefully be in a better position to speculate on the sensori-motor co-ordination mechanisms used in speech production.

One aspect of sensori-motor control that seems relatively accessible to investigation is the role played by sensory feedback from the periphery of the body, in controlling the skilled co-ordination of the many different muscular systems used in speech. Although we can at present only speculate on how the brain decodes the sensory information,we can infer something about sensory feedback by experimentally altering some of the feedback systems and examining the effects on speech output. An experimental investigation into the role of sensory feedback in on-going control of speech and the implications of the results for models of speech performance are reported in detail in Chapters 6 and 7. Once again, the anatomical and physiological background in Chapter 2 proved invaluable in designing this experiment and in interpreting the results in any meaningful fashion. Particularly important was the detailed outline of the types of sensory resources in the oral region and the bio-mechanical constraints imposed on the sensori-motor system by the neuromuscular structures. The results of this experiment will hopefully enable us to come to a better understanding of the neural mechanisms involved not only in controlling one or two articulatory structures,but in co-ordination of all the speech organs. Such aims can only be realized if we exploit the full potential of instrumental techniques such as electropalatography, in providing data necessary for formulating a better model of the peripheral and motor component of a linguistic performance theory. The implications of such investigations may extend even beyond helping us to understand neural control of speech. It may well be that by studying the neuro-muscular systems underlying speech production, we may throw more light on how general voluntary behaviour is initiated, stored, programmed and controlled. What makes speech particularly amenable to such investigation is that we already have a considerable theoretical framework within which we can relatively accurately describe most aspects of the speech output. In some cases, for example aspects of lingual articulation, the theory is, however, still rather incomplete. Hopefully, experimental techniques such as electropalatography will help to fill in many of the gaps in our knowledge.

In summary, the general aims of this thesis are :

(1) To outline a sufficiently detailed anatomical and physiological framework for a more adequate research approach to investigating the myodynamic control of lingual articulation during speech.

(2) To develop electropalatography as an instrumental technique suitable for obtaining vital quantitative and qualitative data on spatio-temporal aspects of lingual articulation.

(3) To outline a parametric phonetic approach to lingual articulation based on information from various instrumental techniques such as electropalatography, and the detailed anatomical and physiological framework.

(4) To use electropalatography in investigating experimentally some aspects of the sensory control of myodynamic speech performance.

The anatomical and physiological framework is outlined in Chapter 2. The three main sections of this Chapter outline some aspects of the physiology of the peripheral nervous system, the biomechanical constraints on muscular activity and the detailed anatomy and physiology of the tongue muscles. Chapter 3 provides a background to the development of electropalatography by reviewing various instrumental methods of analysing different aspects of lingual articulation. The development of the Edinburgh electropalatograph is described in Chapter 4. Chapter 5 discusses the parametric approach to lingual articulation and the implications of such an approach to phonetic theory. Chapter 6 is an account of the experiment investigating sensory control of motor speech performance. Chapter 7 discusses the implications of the results of this experiment for models of speech production, while Chapter 8 includes some concluding remarks on the directions future research in experimental phonetics may profitably take.

CHAPTER 2

ANATOMICAL AND PHYSIOLOGICAL FRAMEWORK FOR RESEARCH ON THE MYODYNAMIC CONTROL OF TONGUE ACTIVITY

INTRODUCTION

The importance to phonetics of a detailed physiological frame of reference for research on the myodynamic control of tongue activity was indicated earlier (Chapter 1). This chapter aims to provide such a framework, by bringing together, in a form readily accessible to phoneticians, relevant physiological information from a variety of different sources. Most of the general background material on the nervous system and the mechanics of muscular activity has been taken from standard reference works in anatomy and physiology. However, details of some of the more technical aspects of myodynamic control, such as the functional operation of muscle spindles and the histology of sensory receptors in the oral mucosa have been obtained from specific and often very recent publications by research workers in neurophysiology, dental anatomy and biomechanics, and from personal communication with experts in these fields. This chapter thus does not pretend to offer original insights into physiological mechanisms; its importance lies rather in creating a synthesis of the available data from a wide range of sources, in order to make available, in a language that phoneticians, as non-specialist physiologists, can understand, a reasonably comprehensive body of relevant physiological background material for the particular research outlined in this thesis and for future research in physiological phonetics.

It would, of course, be quite outside the scope of this thesis to describe in detail the complex anatomy and physiology of the nervous system, so only those functional aspects which seem particularly relevant for speech production are discussed. A considerable amount of space is devoted to certain physiological aspects of the peripheral nervous system including the motor co-ordination of lingual movements and sensory control mechanisms in the oral region. The reason for concentrating on these aspects is twofold; firstly, as far as this writer is aware, this area has been largely neglected by most phoneticians in the past, and secondly, it is of central importance for understanding the implications of the type of research outlined in this thesis.

This chapter is divided into three broad sections: (1.) The nervous system; (2.) Biomechanical constraints on muscular activity; (3.) The detailed anatomy and physiology of tongue activity.

1. THE NERVOUS SYSTEM OF THE BODY

For most descriptive purposes, the nervous system of the body is divided into central and peripheral parts, the central part or central nervous system (C. N. S.) comprising the brain and spinal medulla (Cunningham, 1964), and the peripheral part or peripheral nervous system (P. N. S.), the nerves. However as Cunningham (1964 : 553) points out, the division is somewhat arbitrary because both parts are essential components of a single functioning unit and cannot be clearly separated from each other on anatomical grounds.

At the present time, our knowledge of the role played by the C. N. S. in the control of speech articulation is rather limited. By studying closely different aspects of the more peripheral neural mechanisms, however, we can shed some light on the complexities of the C. N. S. Most attention in this chapter will therefore be focussed on the peripheral nervous system.

The P. N. S. is broadly divisible on an anatomical basis into three parts:

(A) The cranial nerves, which arise from the brain and pass through the skull to be distributed predominantly in the head and neck region,

(B) The spinal nerves, which are attached to the spinal medulla and innervate the trunk and limbs,

(C) The autonomic nervous system, concerned with non-volitional activities such as supplying the blood vessels, sweat glands, viscera, heart, etc.

It is the cranial nerves which are most relevant for a discussion of speech physiology, and therefore will be the exclusive subject of the following discussion.

The cranial nerve system innervates most of the muscles involved in speech articulation; it consists mostly of "mixed" nerves, that is, those containing a very large number of both efferent and afferent nerve fibres, the former sending neural commands in the form of trains of impulses out from the C. N. S. to muscle fibres and the latter reporting back to the C. N. S. information derived from the receptor organs in the skin, mucosa, and muscles. It is thus essential, in understanding the myodynamic control of speech to distinguish between (1.) the efferent (motor) system and (2.) the afferent (sensory) system.

1.1. The Efferent (Motor) System.

1.1.1. Structure of the Motoneurone.

In order to understand how muscles are innervated, it is necessary to describe first the structure of an efferent - or moto - neurone. Fig. 1. shows a schematic diagram of a typical motoneurone. The important functional parts are the cell body or nucleus, the dendrites attached to the nucleus, and the long process of the axon with its various branches or collaterals. The axon is usually referred to as the nerve fibre and can vary greatly in length, from fractions of a millimetre to several metres long. Dendrites are nerve processes similar to the axon but they conduct the neural impulse towards the nucleus, whereas the axons normally conduct the neural impulse away from the nucleus.

On the surface of the cell body and dendrites of each neurone there are a number of specialized junctions or synapses (Sherrington, 1906) where connections are made with other neurones. The nervous system can thus be regarded as a complex interconnecting network of neurones, each one connected to many, sometimes thousands, of other nerve cells, all capable of conducting normal impulses, which

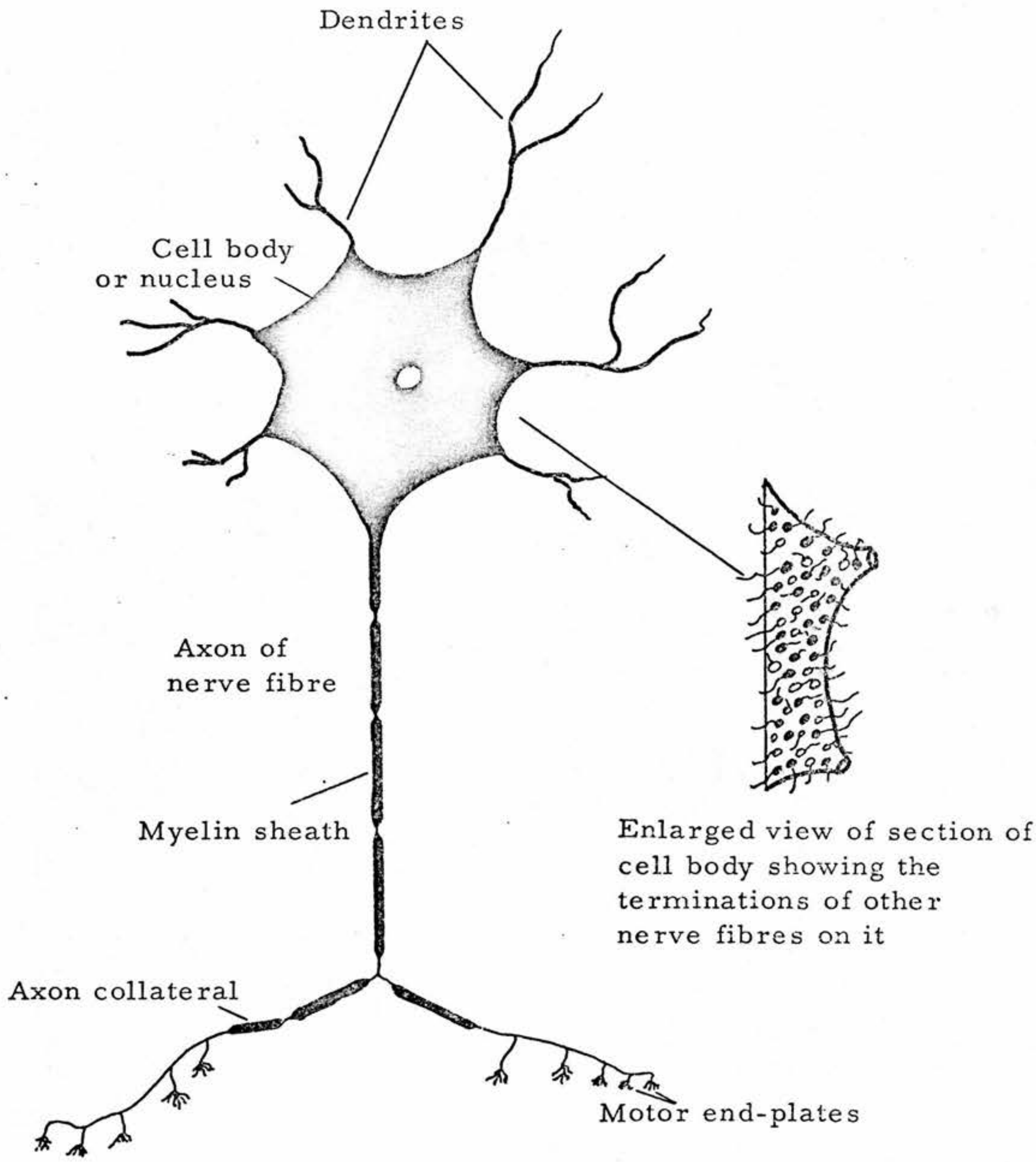


Fig. 1. Semi-schematic diagram showing the main parts of a typical motoneurone and its connections. (after Cunningham, 1964 : 559)

are electro-chemical in nature.

1.1.2. Propagation of the Neural Impulse

The key to an understanding of how neural impulses, in the form of electrical potentials, are transmitted along the nerve fibre, lies in the properties of a semi-permeable membrane which surrounds the axon process. It appears that this membrane is "selectively permeable", i.e. it allows some chemical substancesto pass more readily than others. In an unstimulated resting condition, positive potassium ions are allowed to pass out through the membrane and this results in the inside of the axon being negatively charged with respect to the outside. During excitation, the membrane momentarily becomes much more permeable to sodium ions resulting in an ion-exchange process that reverses the negative membrane potential. Current will then flow immediately to the next negative region of the membrane, so triggering the generation of another action potential. The neural impulses in the form of action potential "spikes" thus travel down the axon as a series of pulses. (For a more detailed explanation of these electro-chemical processes, see Hodgkin (1964).

The rate at which the impulse travels and its transmission time along the axon is of considerable functional significance and depends on a number of factors, including:

(i) the diameter of the axon. It is generally believed that there is a direct relationship between conduction velocity and axon diameter. (Hursh, 1939; Boyd & Davey, 1966; Katz, 1966; Roberts, 1966). As Roberts (1966) says, "There appears to be a good correlation between conduction velocity and fibre-size, the larger fibres conducting their impulses at the higher speeds" (p. 76). The peripheral nerve fibres are usually classified on the basis of their conduction velocities into groups labelled A, B and C, the A group being further sub-divided into alpha, beta, gamma and delta, (Erlanger and Gasser, 1937). The motor fibres to the extra-fusal muscle fibres (see later, section 1.1.4.1.) are largest and have the highest conduction velocity; they come in the alpha category of group A (Roberts, 1966 : 76). Some of these large axons send impulses that travel as fast as 100 metres a second (Eccles, 1965 : 57).

(ii) the type of membrane. Some axons possess a special sheath consisting of cells called Schwann cells wrapped closely about the membrane forming a tube of fatty material called myelin (see Fig. 1). The effect of the myelin sheath is to provide an increase in the speed with which the electrical potential is propagated along the length of the axon (Finean and Robertson, 1958). The axons of cranial nerves innervating the speech musculature are usually of this type.

(iii) the length of the axon. Obviously, the transmission time of the impulse also depends on the length of the nerve fibres. Lenneberg (1967 : 95) illustrates schematically the difference in length of peripheral nerves innervating the speech musculature.

1.1.3. Synaptic Connections Between Neurones

When a motor command in the form of trains of impulses is initiated in the C. N. S., the impulses never travel via one nerve cell only, but traverse many synaptic junctions before reaching the periphery. At each synaptic junction, a chemical substance called acetylcholine is released, facilitating the transmission of the electrical potentials, (Eccles, 1964). The transmission process does not occur instantaneously however; there is a delay called a synaptic delay of about .8 millisecond (Milner, 1967 : 54), so, in general, the more synapses there are in a motor command pathway the longer will be the time taken for the impulses to reach the muscles.

At each synaptic junction, the impulse from a single neurone is usually not enough to effect the synaptic transmission (Eccles, 1958). It requires the concerted effort of a number of neurones to produce the necessary voltage (about .01 volt) to discharge the impulse across the synapse. Many of the neurones making synapses are excitatory in nature, that is, they facilitate the passing of the electrical charges. Some, however, are inhibitory, generating reverse electrical charges and resisting transmission of the impulse. Thus under a barrage of incoming impulses, a neurone must sum the opposing synaptic effects and can fire only when its net excitation exceeds the critical level (Eccles, 1958 : 5). This principle is known as spatial summation (Eccles, 1964).

The process of spatial summation more than almost any other factor gives the nervous system its versatility of response. If excitation at each synapse were obligatory, movement would become stereotyped and incapable of modification. As it is, because of the ability of the C. N. S. to regulate the firing of excitatory and inhibitory cells, usually by means of special interneurones, movements can be continually modulated and varied according to prevailing conditions (Di Salvo, 1961). The process of spatial summation also provides an explanation of why certain responses will usually be made only if two or more circumstances co-exist. Thus in closing off the nasal from the oral passageway, the superior pharyngeal constrictor muscle contracts in unison with the tensor and levator muscles (see Van Riper and Irwin, 1958 : 382).

The ability of the C. N. S. to monitor excitatory and inhibitory effects has important implications for sensori-motor co-ordination of speech,and will be discussed later (section 1. 3.).

1. 1. 4. Innervation of Skeletal Muscle by the Motor System.

1. 1. 4. 1. Structure of Voluntary Muscle.

Every movement of the articulatory organs depends on contraction of muscle, which in turn is mediated by the motoneurones. Voluntary, or striated,muscle is made up of individual muscle fibres of varying sizes and shapes; cylindrically shaped fibres are usually short, while flagelliform or laneolate fibres are longer and usually extend the whole length of the muscle. The diameter of the individual fibres varies from about 10 to 100 microns (1 micron = ·001 mm.), and their length can be anything up to several centimetres (Huxley, 1965).

Within most striated muscles, there are groups of smaller fibres running parallel with the main muscle fibres but gathered together in special receptor organs, called muscle spindles, (see later, section 1.2.2.). These smaller fibres are usually separately innervated from the main fibres and are called intrafusal fibres to distinguish them from the main, or extrafusal fibres. The innervation of intrafusal fibres is of some functional importance in the control of speech production and will be discussed more fully in section 1.3.2.

The individual muscle fibres and so in turn the whole muscle can respond in a number of ways when an appropriate stimulus is applied to it; it may shorten if it can; it may develop tension against a resistance or it may show an increased resistance to extension (Roberts, 1966). The stimulus comes from the nerve fibre supplying the muscle fibre at a region called the muscle end-plate or neuro-muscular junction. Most of the motoneurones supplying extrafusal fibres are large myelinated fibres classified as type alpha while smaller gamma fibres (see above, section 1.1.2.) have also been found in the motor nerves (Leksell, 1945). It is usually thought that these gamma fibres are responsible for innervating the intrafusal fibres but there is a possibility that intrafusal fibres are supplied by large or alpha type fibres as well (Matthews, 1964).

1.1.4.2. The Neuro-muscular Junction and Muscle Action-potentials.

When the propagated action-potential from the motor fibre impinges on the region of the neuro-muscular junction, a complex sequence of electro-chemical processes takes place resulting in an electrical muscle action-potential spreading along the muscle fibre causing it to contract or "twitch" just once. (Eccles, 1952; Katz, 1962, both give a detailed account of the transmission of nerve impulses at the neuro-muscular junction.) These are the basic electrical phenomena from which electro myographic records are derived.

Usually, the entire fibre does not undergo maximal shortening when activated by a single stimulus. The main reasons for this are the mechanical properties of muscle (see later section 2.) including the elastic elements consisting of connective tissues and tendons, etc.

For full shortening to occur, the active state of the muscle must be maintained by repetitive stimulation (Hill, 1949). Under normal conditions this is what happens; the result is sustained rather than twitch-like muscular activity. This sustained contraction is called tetanic contraction, and it produces shortening of the fibre which may be two or three times as great as the single twitch; thus it is far more efficient (Cooper and Eccles, 1930).

After contraction of the muscle fibre, there is a short period of time (the "refractory" period) while the original chemical balance is restored. The frequency of discharge of the action-potential is limited by this refractory period. Impulses arriving too fast (i.e. before the chemical balance is restored) will usually have no effect. In actual muscular contraction, however, this is perhaps avoided by some sort of inhibitory mechanism, for instance, the Renshaw loop control connected to the moto-neurones (Renshaw, 1941).

1.1.4.3. The Motor Unit

There are more than 100 muscles involved in some aspects of the articulatory process, containing several million muscle fibres, and only a fraction of that number of myelinated cranial nerve fibres, so obviously all the individual muscle fibres cannot each be supplied by a separate nerve fibre. The concept of a motor unit as the functional unit of muscular activity (Liddell and Sherrington, 1925) has thus been introduced into physiology, the unit consisting of a single motoneurone, its axon and the group of muscle fibres innervated by branches of this axon. By virtue of the anatomical relationship, electrical activity in the nerve cell of a motor unit leads to activation of all the muscle fibres in that unit. Thus a single impulse arriving via the nerve fibre of a motor unit and impinging on the muscle end-plates of each muscle fibre in that unit will cause all the muscle fibres to contract just once. Increased tension in the muscle will be accompanied by increasing rate of firing of the motor units and a state of tetanic contraction may result.

The number of muscle fibres in a motor unit (the innervation ratio) varies from muscle to muscle according to the role they play in motor activity. In general, muscles requiring delicate adjustments of movement, for example the intrinsic tongue muscles (see below Section 3.1.3) have a low innervation ratio i.e. a small number of muscle fibres for each motor unit. This, added to the fact that each motor unit is under separate neural control via the controlling motor nerve fibre, means it is possible to achieve delicately controlled tongue configurations, for example in the production of the grooved fricative [s].

Not only does the number of muscle fibres in a motor unit vary, but the distribution of motor units throughout the muscle often varies. The motor units may be distributed evenly throughout the muscle but they are often gathered into groups in certain parts of the muscle. This differential distribution is obviously of considerable importance in interpreting the electrical activity at a specific point in the muscle (e.g. by electromyographic techniques) and will be discussed later in Chapter 3.

Since the stimulated muscle fibres in a motor unit either contract or do not - the all-or-none principle - so obviously the motor units supplying a muscle do not normally all work together at the same time. If this were the case, the muscle would contract as a series of violent jerks and controlled precise gradation of contraction as is necessary for certain speech articulations would be impossible. In the course of normal muscular activity, however, the responses of the different motor units are out of phase. This may be due to different thresholds to excitation in the motoneurone pool (i.e. the collection of motoneurones for any one particular muscle, (see Milner, 1967) or different diameters of nerve fibres carrying impulses to the muscle fibres (Bessou, Emonet-Dénand and Laporte, 1963). Whatever the cause, the asynchrony of the arriving motor impulses and the consequent randomization of motor twitches of individual motor units result in an overall graded smooth contraction of the whole muscle, essential for accurately controlled articulatory movements. It is interesting to note here that because the motor units in a muscle have different thresholds to excitation, more and more motor units will be "recruited" as the speaker needs to increase the tension in the muscles (cf. "recruitment of end-organs" later, section 1.2.1.)

To sum up therefore, increase in muscular effort is accompanied by two effects:

(i) increase in the repetition frequency of activity cycles in individual motor units, and

(ii) increase in the number of units showing activity.

Because of (ii) it turns out that the detailed analysis of electromyographic records from surface electrodes is often highly unreliable because they are composed of so many components all mixed up together. This is particularly true of complex muscular systems such as the tongue, and most electromyographic studies on the tongue using surface electrodes have been severely limited by this fact (MacNeilage and Sholes, 1964).

1.2. The Afferent (Sensory) System

1.2.1. General Structure of Sensory Neurones and Receptor Organs

Afferent neurones are similar in general structure to motoneurones (see Fig. 1) but unlike motoneurones, they usually have their nuclei close to the periphery of the body and conduct neural impulses from receptor organs in the skin, mucosa or muscles towards the central nervous system. These receptor organs may be separate receptor cells connected to the sensory fibre or may be dendrite-like terminals of the sensory fibre itself. They act like "biological transducers" (Loewenstein, 1960), generating patterns of neural impulses, which are transmitted back to the C.N.S, and result in sensations such as heat, cold, touch, pressure, etc. Often each sensory receptor sends messages in only one sensory nerve fibre but single fibres may be connected to a number of receptors in which case the whole group is called a sensory unit. The analogy with the motor unit is quite clear.

Electrophysiological experiments have shown that stimulation of receptors results in a flow of electrical current that excites the nerve fibres. The intensity and duration of the applied stimulus is reflected in the repetition frequency of the electrical potential in the sensory fibre (Adrian, 1928). Thus the message sent to the C.N.S. is coded in terms of a series of identical action potentials in particular nerve fibres of varying frequency.

A second way in which the intensity of the stimulus affects the afferent discharge is in the number of sensory receptors active. As the stimulus increases, more sensory units become active, a process known as "recruitment of end-organs" (Fulton, 1955). This principle may have important applications in localizing stimuli more accurately (see later, Chapter 6).

1.2.2. Sensory Resources in the Oral Region

Receptors in the oral region can be divided into two general categories according to whether they are normally excited by mechanical or chemical means. Mechano-receptors respond to various kinds of mechanical distortion arising, for instance from the tongue touching the palate or teeth, by generating a depolarizing current in the sensory fibre (Gray, 1959). Chemo-receptors, such as those responsible for detecting taste, as their name implies, respond to chemical changes and as such are probably not important in controlling speech articulation. It should be noted here that there appears to be no direct correlation between specific receptors and sensory modalities such as touch, pressure, heat, cold, etc. It seems rather that the nature of oral sensation is determined by the pattern and intensity of nerve impulses and not by the stimulation of specific receptors (for a more detailed discussion, see Weddell, 1960 and Woodford, 1964).

Most of the oral mucosa and particularly the tongue surface is very well supplied with many different types of mechano-receptors (Gairns, 1953; Dixon, 1961). Although it is probably true to say no two receptors are exactly alike (Ormea and Re, 1959), nevertheless, on the basis of their morphological structure, a broad classification of receptors into diffuse (free) endings and compact (organized) endings is sometimes made (e.g. by Weddell, 1960; Winkelmann, 1960).

It has been tentatively suggested (Hardcastle, 1970) that there may be some functional significance in this classification for the sensory control of speech articulation, the free endings, particularly the superficial free endings, subserving a general sensation of touch and the organized endings allowing more discriminative touch - a high degree of tactile acuity. A clue to the function of the receptor organs may lie in their morphological structure and their position in the oral mucosa.

The free endings are fine, diffuse overlapping terminal filaments, which interweave with one another throughout the oral mucosa (Dixon,1961, 1962). They arise from branching myelinated fibres of varying diameters which form dense networks or plexuses, (Kantner, 1957). Fibres from the superficial plexus often penetrate into the epithelium (see Fig. 2), some reaching the most superficial epithelial layers; (Niihata (1938), reported this particularly in the tip region of the tongue). It should be noted that there are considerable technical difficulties in demonstrating the presence of fine nerve fibres in the epithelium; there is quite a lot of evidence, however, that fibres do in fact penetrate at least into the base of the epithelial membrane (Sprinz, 1970).

Fig. 3 shows a schematic diagram of three nerve fibres showing overlapping fields of free endings in the tongue dorsum. Because of the network arrangement of the fibres, stimulation at any point, for example, point X on the dorsum will necessarily activate a number of fibres. No two points, however, come equally within the territory of the same nerve fibres (see Fig. 3). Thus if the epithelium is touched at X it is within the receptive area of all three nerve fibres. The pattern of discharge for area X is therefore unique in that no other point in the whole body is exactly in that position in the fields of these three nerve fibres. Békésy (1967 : 38) discusses this principle called <u>lateral inhibition</u>, which enables the point of stimulation to be localized in the sensory cortex. It is interesting to note that the inhibition is stronger for stimuli with rapid onsets and this produces a greater degree of tactile acuity (Békésy, 1967 : 46).

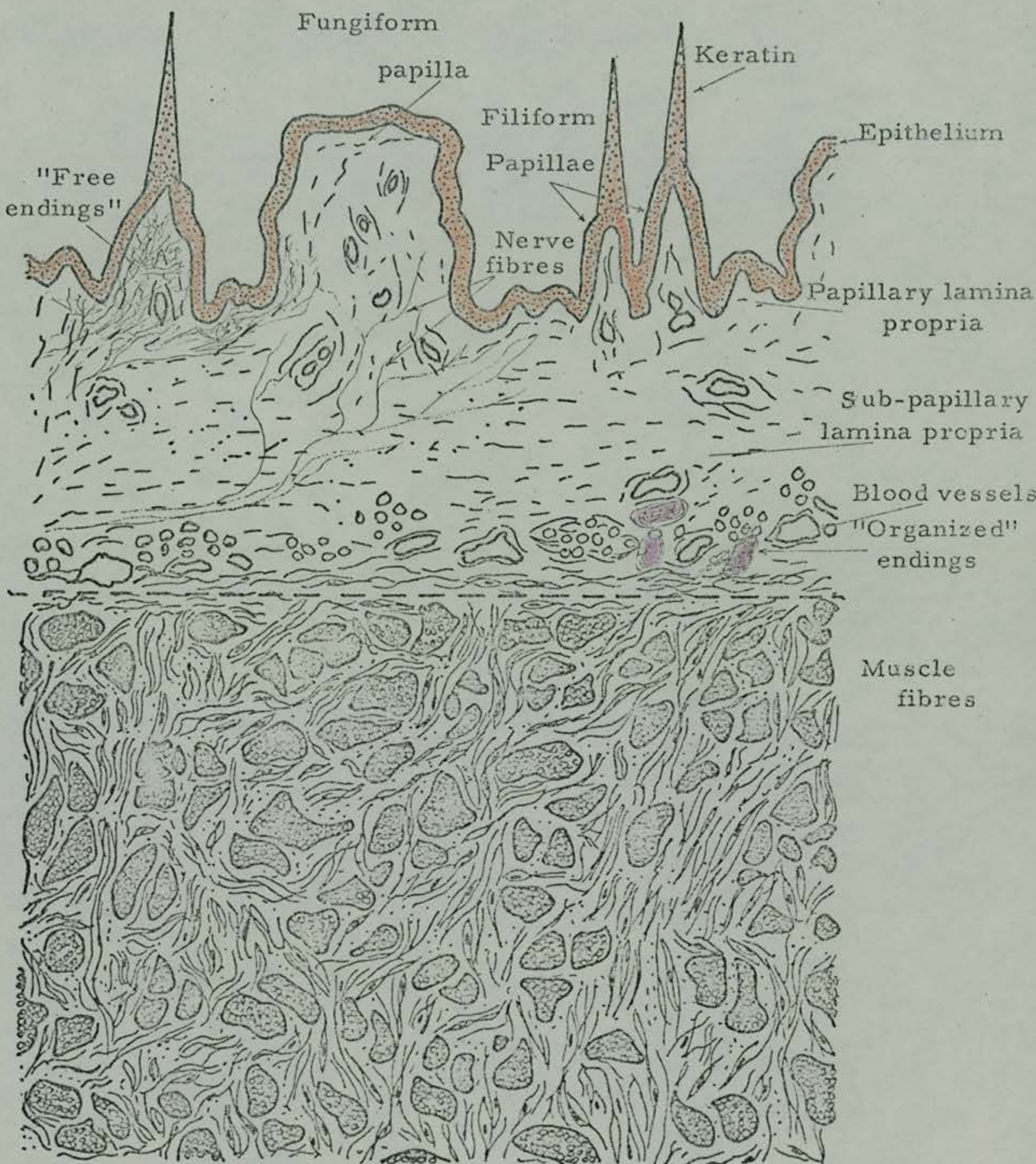


Fig. 2. Highly magnified transverse (coronal) section through the front part of the tongue, showing the papillae, epithelium, lamina propria and muscle fibres. Some sensory receptors including free-endings and organized endings are drawn in to indicate the appropriate positions in which they probably occur.
(After Cunningham 1964 : 387)

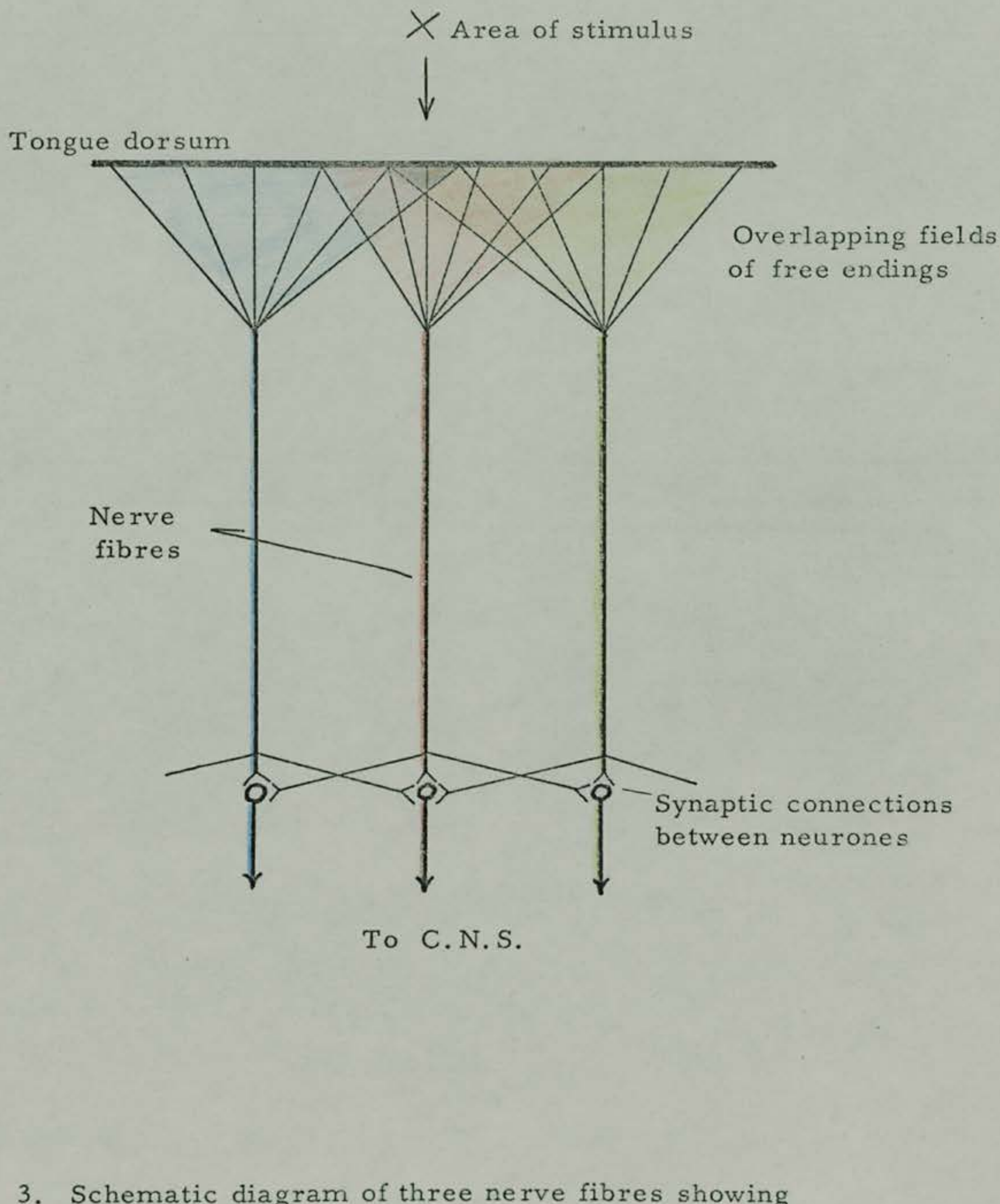


Fig. 3. Schematic diagram of three nerve fibres showing overlapping fields of "free endings" in the tongue dorsum.

The organized sensory receptors, unlike the free endings, are usually well defined morphologically distinct structures, consisting normally of tissue capsules, through which a nerve fibre pursues a complex course sometimes dividing into minute fibrils (Krause, 1861, cited by Strughold, 1925; Cauna, 1956). The structures of two types of encapsulated endings, Krause end-bulbs (Krause, 1860) and Meissner corpuscles (Cunningham, 1964 : 791), are illustrated diagrammatically in Fig. 4. In general, because of their relatively large size, these organized receptors in the tongue are situated below the superficial free endings particularly in the subpapillary lamina propria (see Fig. 2). Most of these receptors, particularly those of the Meissner corpuscle type, respond to the slightest degree of deformation and stop discharging abruptly, directly the movement ceases (Weddell, 1960). The impulses are discharged through large sensory nerve fibres, measuring on an average 8-10μ in diameter (Murphy and Cameron, 1967). The fibres supplying these receptors are thus of slightly less calibre than the motor fibres supplying the main muscle fibres. It may be that these organized receptors, responding accurately to different degrees of pressure, may play some important part in sensori-motor co-ordination of speech (see later section 1. 3.).

The mechano-receptors so far mentioned are situated above the level of muscle fibres in the tongue (see Fig. 2). There are a number of types of receptors however, which are situated within the oral musculature, in the capsules of joints, and attached to the periodontal membranes of teeth. The receptors in the muscles and joints respond to stretch on the muscles or movement of the joints and are usually referred to respectively as muscle spindles and joint receptors. The receptors attached to the periodontal membrane are known as the periodontal receptors. The neurophysiology of joint receptors in the temporomandibular joint, which is the main joint associated with speech articulation in the oral region, has been discussed in detail elsewhere (e. g. Kawamura and Majima, 1964; Greenfield & Wyke, 1966;

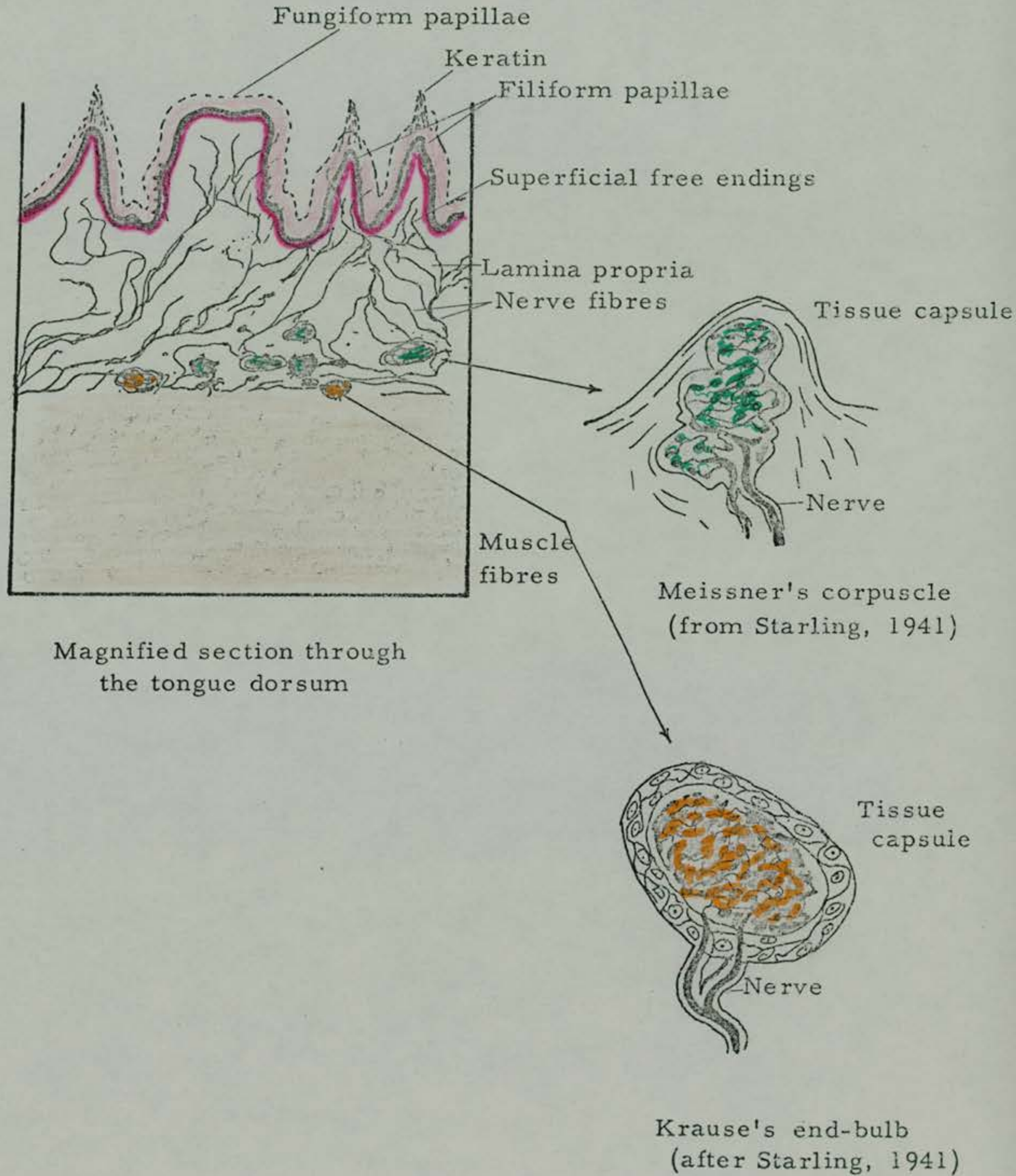


Fig. 4. Diagrammatic representation of two of the so-called "organized" endings, Meissner's corpuscles and Krause's end-bulbs, and their probable distribution in the deeper layers of the lamina propria.

Kawamura, Majima & Kato, 1967; Klineberg, Greenfield & Wyke, 1970) so will not be described at length here. Suffice it to say that the joint receptors respond directly to stretching on the capsule in the joints usually caused by the action of the mandibular muscles. Periodontal receptors and muscle spindles probably play an important role in the myodynamic control of speech so they will be discussed at some length.

Periodontal receptors are the fine filament endings attached to the periodontal membrane of teeth and respond to the slightest touch on the teeth (Scott and Symons, 1958). As the pressure sense of these receptors is extremely delicate, corresponding in sensitivity to some of the encapsulated receptors in the tongue (Pfaffmann, 1939), they would certainly respond to pressure exerted by the tongue during speech articulation and thus may play some part in myodynamic control. As far as this writer is aware, the presence and possible importance of periodontal receptors has not been mentioned before in the phonetic literature.

The other type of receptor mentioned, the <u>muscle spindle</u> has been located by a number of investigators in the intrinsic and extrinsic muscles of the tongue (e.g. Cooper, 1953; Hosokawa, 1961). Although traditionally associated with stretch reflex activity in the limb muscles maintaining body posture, it has recently been suggested (e.g. by Öhman, 1967; MacNeilage, 1970) that the spindle has a possible important function in the myodynamic control of speech production, so it will now be described in detail.

To understand the functions of the spindle, it is necessary to outline in some detail its morphological structure. Because of its extreme complexity, however, it is only possible here to discuss some of the relatively uncontroversial parts of the spindle and their possible functional significance. Most of the following outline is derived from papers delivered in a number of recent symposia on the subject of muscle spindles (Barker, 1962; Granit, 1966; Andrew, 1966) and from several notable reviews on the subject that have been published (e.g. Granit, 1955; Hunt and Perl, 1960; Cooper, 1960; Matthews, 1964;

Jansen, 1966).

A semidiagrammatic representation of a typical muscle spindle is shown in Fig. 5. Within the connective-tissue sheath of the spindle, lie a number of small intrafusal fibres (see above section 1.1.4.1.) running parallel to the main extrafusal fibres of the muscle. The intrafusal fibres (up to ten in number) are bound together by the sheath which, near the middle of the spindle bulges out in a small swelling containing a lymph space. There seems to be general agreement now that most spindles contain two types of intrafusal fibres distinguished by the arrangment of their nuclei in the central lymph space. In fibres of one type, called nuclear-bag fibres, there is an aggregation of nucleii into a close-packed clump. In fibres of the second type, called nuclear-chain fibres, the nucleii are arranged in single file (see Fig. 5). For a full discussion of the morphology of the two intrafusal fibre types see Boyd (1962).

Intimately connected to the intrafusal fibres are two types of receptors called the primary and secondary endings. Each spindle has one and only one primary ending; it may however have a number of secondary endings. The primary ending consists of spirals around the central parts of both the nuclear-bag and nuclear-chain fibres and has a large afferent fibre (sometimes called type I) with high conduction velocity. (Murphy and Cameron, (1967), state that the fibres from the primary endings are comparable in size with the alpha motoneurones; this makes them larger than the sensory fibres supplying other mechanoreceptors, e.g. those responding to touch and pressure.) Because of its histological shape, the primary ending is often referred to as an annulospiral ending. Secondary endings lie mainly on nuclear-chain fibres (Roberts, 1966), although Boyd (1962) has them connected to the nuclear-bag fibres as well. They usually take the form of sprays of fine fibre branches sending their impulses via smaller Type II fibres.

Because of the anatomical arrangement of the primary endings and the structure of the central part of the spindle, their receptors respond both to the degree of stretch of the central, non-contractile part of the spindle and to the rate-of-change of stretch as well (Matthews, 1933)

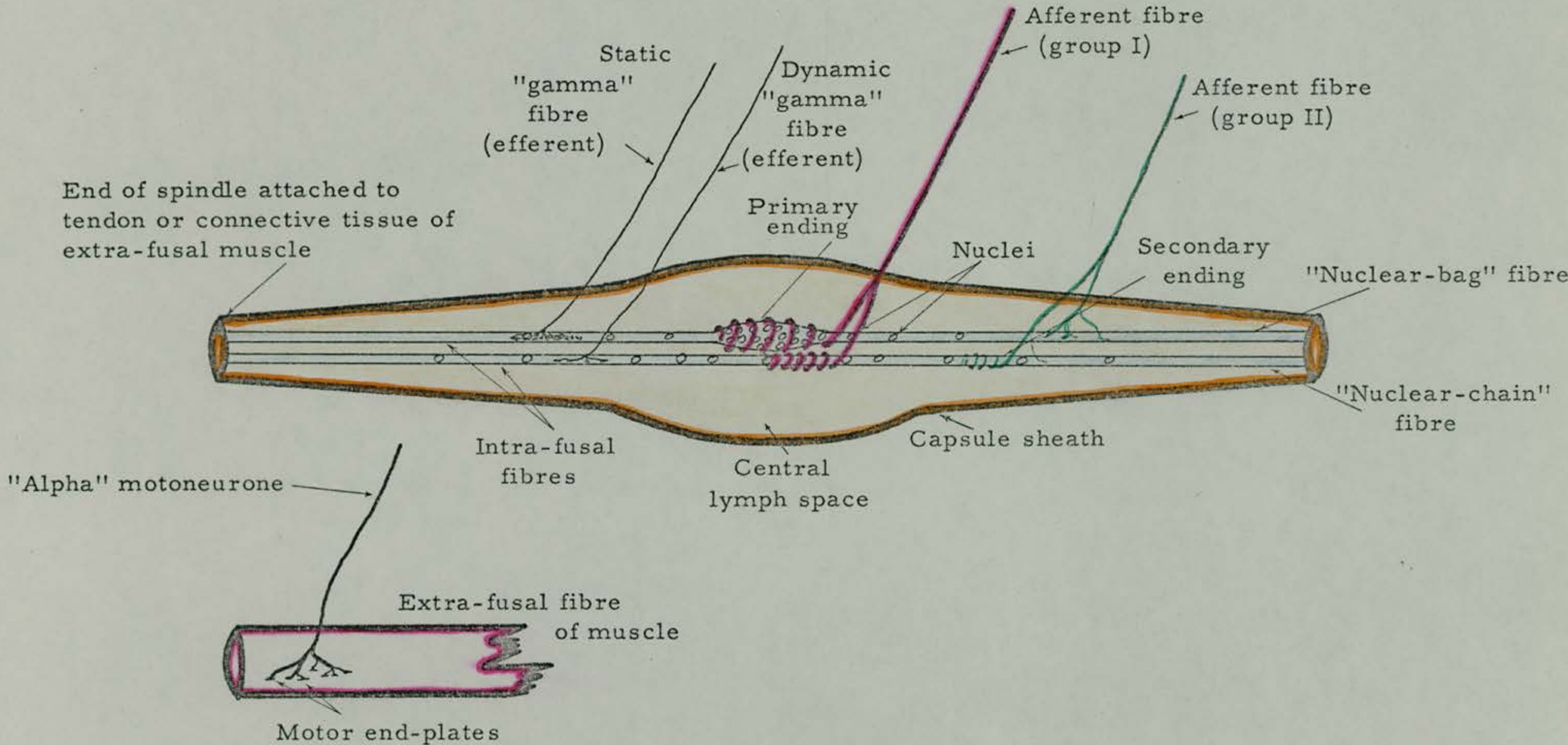


Fig. 5. Highly simplified diagram of some parts of a typical muscle spindle (after Boyd, 1962).

The response to maintained stretch, the static response, increases approximately linearly with the length of the muscle (Eldred, Granit and Merton, 1953; Jansen and Matthews, 1962). The response to velocity of stretch is called the dynamic response and increases in proportion to the rate-of-change of muscle length. These two components of primary ending response, the static and dynamic, may have important functions in the control of speech production (see below, section 1. 3. 2.). As far as secondary endings are concerned, it seems likely that they are much less sensitive to velocity of stretch than the primary endings (Bessou and Laporte, 1962). To static extension, however, the firing frequency is comparable with that of the primary endings, increasing approximately linearly with muscle length (Harvey and Matthews, 1961). The precise function of the secondary endings is a little uncertain at the present time (Kuczynski , 1970) so they will not be discussed in any great detail here.

Primary endings, therefore, respond to both degree of stretch and velocity of stretch of the central part of the spindle. Investigations have shown (e. g. by Liddell and Sherrington, 1925) that the primary afferent fibres of the spindle make direct synaptic connections with motoneurones to the muscle in which the spindle is situated. Thus any activity in the large Type I afferent fibres from primary endings may result in a direct firing of the main alpha motoneurones to the extra-fusal fibres causing the muscle to contract. This mechanism is the basis of the so-called stretch reflex loop which can be seen clearly in its rudimentary form in the familiar knee jerk. Fig. 6. shows a typical diagram of a stretch reflex loop in the spinal system. It is probable that a similar mechanism occurs in the spinal medulla with the spindle afferent fibres from tongue muscles (Sprinz, 1970).

Now stretch on the central part of the muscle spindle, which causes the firing in the afferent fibres can be brought about in a number of ways; either as a result of lengthening of the main extra-fusal fibres to which the spindle is attached (see Fig. 5.) or as a result of contraction of the intra-fusal fibres within the spindle (Hunt and Kuffler, 1951).

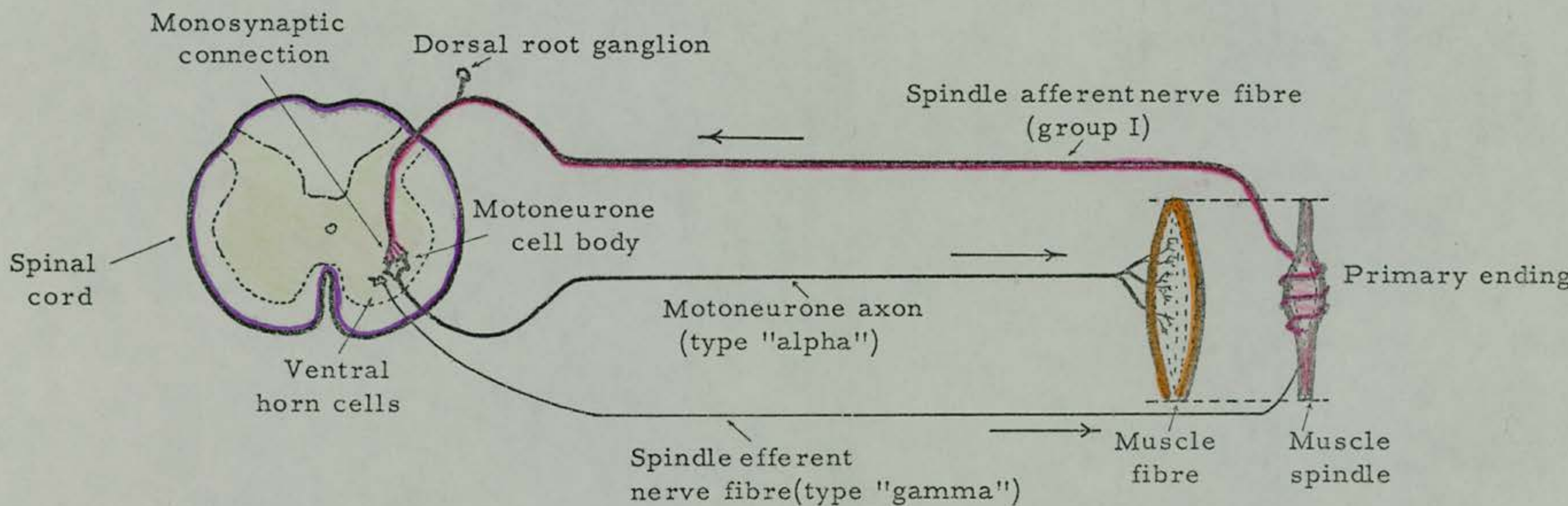


Fig. 6. Schematic diagram of basic stretch reflex loop for the spinal system. The arrows refer to the direction of propagation of the neural impulses.

If the muscle is lengthened, the increasing firing of the primary afferent fibres will reflexly increase activity of the motoneurones to the extra-fusal fibres of the muscle because of the stretch reflex loop (Fig. 6.). Thus lengthening of the muscle may be opposed by contraction and a state of equilibrium will be achieved. If the contraction of antagonistic muscles or whatever it is that is causing the muscle lengthening is relaxed, the primary ending firing will decrease rapidly, so diminishing the effect of the stretch reflex loop. Because of this reflex activity, the primary afferent and alpha motor system is said to constitute a servo-system with obvious importance, for instance, in maintaining body posture against the opposing force of gravity. This reflex activity is said to take place in the co-ordinating centres of the brain, probably the cerebellum (Matthews, 1964) so is a largely automatic activity. Also, because the primary impulses are sent via large afferent fibres, which have high conduction velocity, the reflex loop will be extremely fast acting (Milner, 1967 : 56). This rapidity may be important for controlling fast movements required for speech production.

The other means by which stretch can be exerted on the central part of the spindle is by the contraction of intra-fusal fibres. Originally, this was thought to result from firing of small gamma motoneurones (see Section 1.1.4.1.). It seems now, however, that for some spindles at least, the intra-fusal fibres may also be innervated by collaterals of large alpha motoneurones which supply the ordinary extra-fusal fibres (Bessou, Emonet-Dénand and Laporte, 1963, 1965). The functional significance of this alpha innervation is difficult to assess in the light of present knowledge. Far more information is needed about the frequency of occurrence of this alpha innervation in different muscles (Jansen, 1966). The picture is further complicated by the presence of at least two types of gamma efferent fibres distinguished by their effects on the primary ending discharge (see Fig. 5.) Dynamic gamma fibres increase the dynamic sensitivity of primary endings i.e. their response to velocity of stretch, whereas static gamma fibres have little or no effect on dynamic sensitivity. Both types excite the receptors in a similar way at constant muscle length (Crowe and Matthews, 1963). Some investigators have observed (e. g. Roberts, 1966 : 70) that dynamic gammas are responsible mainly for innervating the nuclear-chain fibres and static gammas innervate the nuclear-bag fibres, although both types of fibres may sometimes occur in both types of intra-fusal fibres.

There is general agreement now among physiologists that the higher parts of the nervous system can control gamma motoneurones independently of the alpha motoneurones and that they can also exert separate control over the gamma motoneurones of different muscles (Matthews, 1964 : 270). Also,because of the anatomical separation of static and dynamic gammas, it seems likely that they are separately controlled as well. The ability of the C. N. S. to exert independent control over these different types of fusimotor fibres has important implications for the co-ordination of muscular activity, which will be discussed in Section 1. 3. 2.

It can be seen from the above outline, that activity of the fusimotor fibres reflexly causes firing in the main alpha motoneurones and so muscular contraction (see Fig. 6.). Some investigators (e. g. Kuffler and Hunt, 1952) have suggested that the importance of fusimotor fibres was "to maintain the afferent flow from spindles in spite of a certain amount of mechanical shortening" of the spindle (Matthews 1964 : 274). It was shown earlier how primary ending discharges decreased rapidly if stretch on the muscle was relaxed suddenly. If, however, fusimotor control were maintained, the sensory and reflex functions of the spindle could be preserved during the rapid shortening.

An alternate suggestion which, because of its considerable theoretical importance in the myodynamic control of speech has attracted widespread attention is that the muscle spindles and fusimotor fibres form part of a "follow-up length servo" by means of which a muscle can be reflexly set to any desired length. The suggestion was originally formulated by Merton (1953) and has since been discussed at length by a number of different investigators in physiology (e. g.

Partridge and Glaser, 1960; Roberts, 1966) and in phonetics (Öhman, 1967; MacNeilage, 1970).

The basic argument involves the operation of the stretch reflex loop discussed above. It was seen how, by reflexly opposing lengthening of the muscle by contraction, the stretch reflex acted like a servo-system (see Fig. 6.), thus maintaining the muscle at a fixed length only. Fusimotor discharge provides one way in which the muscle can be set reflexly to a variety of lengths. Any increase in fusimotor activity will cause a corresponding increase in the frequency of discharge from the primary endings, and this will reflexly cause the muscle to shorten until the discharge of the primary ending is reduced to its previous value. (Primary ending discharge decreases, of course, with muscular contraction both in the presence and absence of fusimotor activity). Thus, if a fusimotor command is sent appropriate to the desired length of the muscle this length will be automatically achieved irrespective of the length of the muscle at the beginning of the movement. This principle has been specifically suggested by a number of investigators as one of the possible means of solving the problem of motor equivalence i.e. the fact that we almost never perform an act such as an articulatory movement, exactly the same way twice; there are always minor or major variations on the movements made, depending on local conditions at the time, etc. (Milner, 1967; MacNeilage, 1970). As Milner (1967) says, "The muscle feedback mechanism.... ensures that the same end result is produced whatever the local conditions at the muscle concerned, and it achieves this result without the necessity for a whole range of different sets of instructions from the immediately higher motor centres" (p. 45). The local conditions may include not only the tension and length of the muscle before the movement but changes in tension, etc. as a result of some external force during the movement. Compensation for any external force will take place by means of the stretch reflex servo-system.

In this view, therefore, the fusimotor fibres are seen as a pathway for initiating movements, by their effects on the muscle spindles rather than as a compensation for the effects of movement upon the spindle.

There is some evidence to suggest that discharge of gamma motoneurones may precede that of alpha motoneurones in the same muscle (Cooper,1960 : 412; Matthews, 1964 : 275) but this is by no means conclusively established. It seems reasonable to assume that for any voluntary movement, e. g. a particular speech articulation, sufficient gamma and alpha activity is sent appropriate to the target position and velocity of movement. As Matthews (1964) says, "the alpha route would perhaps be most efficiently employed in conjunction with sufficient fusimotor activity to prevent any decrease in spindle discharge occurring during the contraction, this would be achieved if the relative amounts of alpha and gamma activity were adjusted to be appropriate for the velocity of shortening 'expected' under any particular set of conditions. Then if shortening proceeded faster than 'intended' by the higher centres it would be slowed by servo action and if shortening were hindered by some unexpected load it would be speeded up by servo action" (p. 277).

The spindle thus can perhaps be regarded as playing a dual role in not only providing moment-to-moment information on the degree of tension and rate of change of tension in the muscle,but also acts as an essential element in a servo-mechanism system by means of the stretch reflex loop. The possible importance of the muscle spindle in myodynamic control of speech will be discussed in section 1. 3. 2.

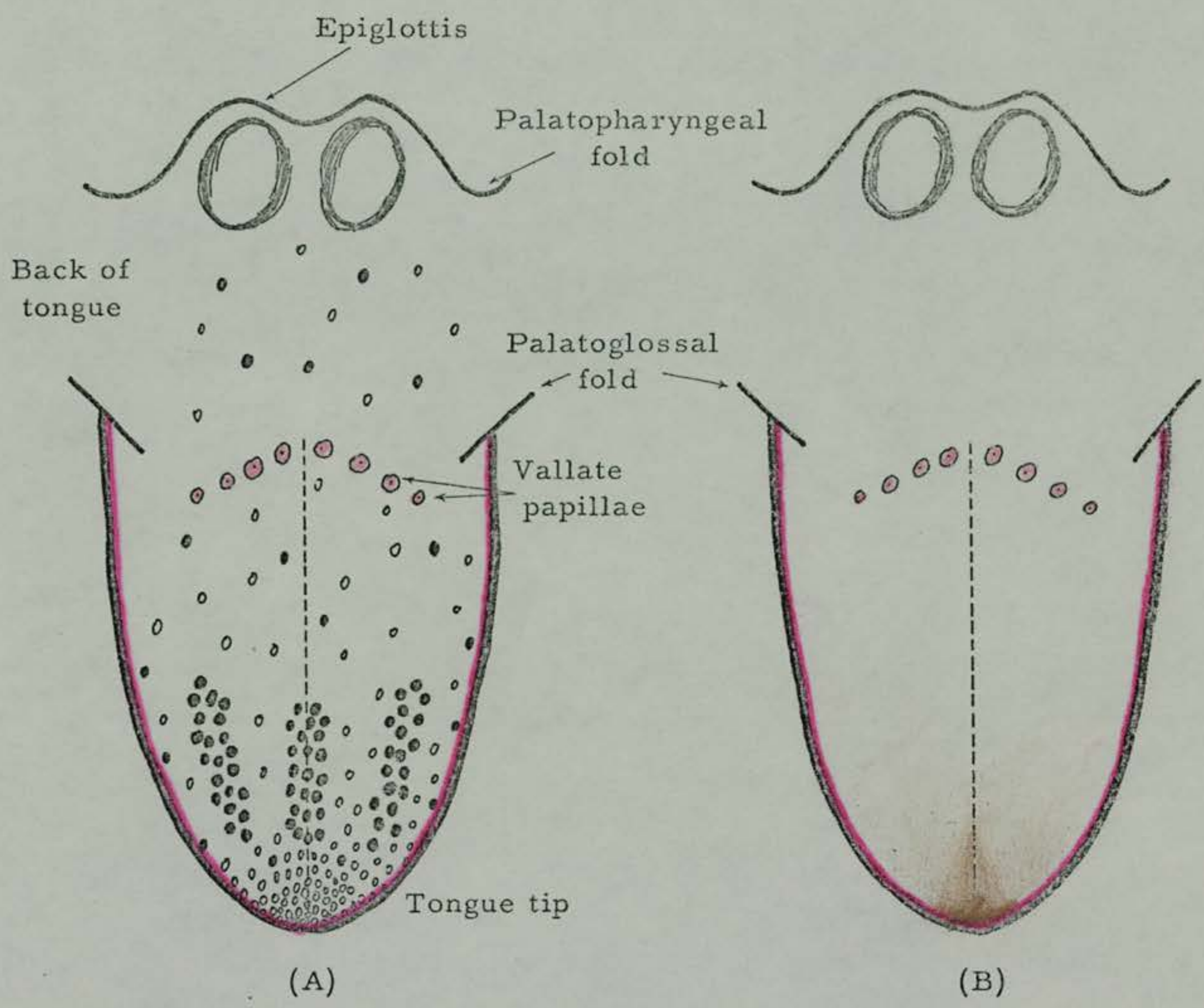
1. 2. 2. 1. Distribution of Sensory Resources in the Oral Region.

Some recent histological studies (e. g. Cooper, 1953; Grossman, 1964b: Dixon, 1962) have indicated that the sensory receptors mentioned in the previous section are not evenly distributed throughout the oral region. After a review of the histological literature relating to sensory receptors in the oral region, Grossman (1964b) concludes that there is "a progressive decrease in the frequency of sensory endings from the front to the rear of the mouth in humans" (p. 132). This progression is particularly noticeable in the tongue, where the tip seems better endowed with sensory receptors subserving tactile and pressure sensations than any other part of the oral system (Grossman and Hattis, 1967). It is interesting to note also that this progression seems to apply to the oral tissues of other species as well. (Kamada, 1955; Dixon, 1962).

Research by Cooper (1953) suggests also that there is a differential distribution of muscle spindles in the tongue. She found most spindles in the superior longitudinalis muscle near the midline and in the front third of the tongue, and in the transversus muscle in the mid-region towards the lateral borders. It is significant that the greatest density of muscle spindles has been found in those parts of the muscles which are plausibly thought of as needing the maximum delicacy of adjustment in the production of complex articulations such as [s], [tʃ], etc. (see Chapter 5, for a detailed discussion of the concept of "complexity" of articulation).

The large number and variety of other sensory receptors particularly the tactile receptors of both diffuse and organized types in the anterior part of the tongue, suggests that this part of the organ is capable of a considerable range of sensory discriminations, many of which are probably important for the control of speech production. The delicacy of tactile sensory discriminations in the front of the mouth is well illustrated by two-point discrimination tests which show an increasing degree of tactile acuity towards the lips (Grossman, 1964a). In addition, oral stereognosis studies (Bosma, 1967) have shown that the anterior two-thirds of the tongue are primarily important in oral discriminations probably involving an integration of both tactile and proprioceptive (i. e. muscle spindle and joint) receptors (Shelton, Arndt and Hetherington, 1967 : 223). It is interesting to note in this regard that Penfield and his associates (Penfield and Boldrey, 1937) noted frequent responses involving the front of the tongue and lips after electrical stimulation of the cortex, but relatively infrequent responses in the back of the tongue. The possible distribution of sensory resources in the tongue is shown schematically in Fig. 7.

The comments above in this section suggest that some articulations made with the anterior part of the tongue, may utilize a greater range of sensory resources and so be capable of more delicate control than articulations made with the back part of the tongue. The implications



Distribution of some sensory receptors in the tongue (based on Cooper, 1953; Grossman, 1964b).

Muscle spindles
Other receptors
incl. "organised" receptors

Map of tactile acuity (based on Grossman, 1964 (a), Ringel and Ewanowski, 1965).

More sensitive
Less sensitive

Fig. 7. Two schematic diagrams showing (A) the (hypothesized) distribution of some sensory receptors in the tongue and (B) the (hypothesized) relative tactile acuity of the tongue surface.

of this will be discussed more fully in Chapter 5.

1.3. Sensori-motor Co-ordination.

1.3.1. Importance of Sensory Feedback Control of Speech Production.

So far in this chapter it has been shown how the motor system transmits neural impulses to the muscles from the C.N.S. and how the receptor organs at the periphery of the body or within muscles send "back" via the afferent nerves different sorts of information about the characteristics of the stimuli applied to them. It remains to be shown how in fact the C.N.S. makes use of this sensory system to co-ordinate movements. The importance of sensory feedback for motor co-ordination has not always been recognized. Early research workers believed there was a one-to-one relationship between discrete chains of motor impulses from the C.N.S. and equally discrete movements at the periphery. As Bernstein (1967) notes, "physiologists of the last century (e.g. Munk, Bekhterev) saw the motor area of the cortex as a sort of keyboard on which somebody's hand, in sovereign control, described the program for a given motor stereotype. The pressing (excitation) of one of these cell buttons always brought about a given degree of flexion at a given joint, the pressing of a second brought about extension, etc." (p. 145). This is, of course, far too simplistic a view of the operation of the nervous system; it does not take account of the multiplicity of motor patterns depending on the state of the muscle at any given time, due to external forces such as gravity, friction, etc., or of the complex neural pathways involving many synapses (see above section 1.1.3.).

It is quite clear now that the only way motor co-ordination is possible is by constant sensory feedback from receptors at the periphery. As Bernstein puts it, (1967 : 106-107), "The motor effect of a central impulse cannot be decided at the centre but is decided entirely at the periphery; at the last spinal and myoneural synapse, at the muscle, in the mechanical and anatomical changes of forces in the limb being moved, etc.... The central effectors achieve co-ordination of movements only by plastically reacting to the totality of the signals from the afferent field, adapting the impulses transmitted to the situation that actually obtains at the periphery."

It was indicated above how sensory resources provide the C.N.S. with continuous information on the position, acceleration and velocity of the vocal organs. It is conceivable that the C.N.S. integrates reports from different receptors and receptor-types to give a dynamic "schema" or running plot of the state of the vocal organs: (cf. the "body schema" of Head and Holmes, (1920), which they describe as an unconscious physiological record of the body posture). There are two ways in which the C.N.S. probably makes use of information of this dynamic schema type: (a) By means of such systems as reflex mechanisms (see, for instance, stretch reflex loops discussed in section 1.3.2.) and (b) By comparing the running plot of an actual articulation with the running plot of sensory information that the brain would expect from successful execution of the normal appropriate articulation. If these two schemata don't match this may be one way in which the brain may decide that a speech error has occurred.

Exactly how these complex integration processes are carried out in the C.N.S. is not yet fully understood. A closer view of the feedback resources and their possible function in speech articulation may, however, throw some light on this problem.

1.3.2. Different Types of Feedback Used in Speech Articulation.

Two main types of sensory feedback circuits, the exteroceptive and proprioceptive, are probably used for the myodynamic control of speech. The exteroceptive circuits include auditory feedback, reporting on bone and air conduction of vibratory and acoustic stimuli in the ear, and tactile feedback reporting on contacts between different vocal organs, for example the tongue against the palate. The proprioceptive circuits report on the tension of the muscles and movements of the joints.

The auditory feedback system has been comprehensively described elsewhere (see bibliography in Békésy, 1967), so discussion about feedback systems will be limited in this thesis to those systems directly relevant to sensations arising in the organs comprising and affecting the vocal tract only i.e. (a) the tactile system and (b) the proprioceptive system.

(a) The Tactile System.

The receptors in the tactile circuit include the free endings and organized endings discussed in the first part of section 1.2.2. Most of the sensory fibres supplying the tactile receptors in the front part of the tongue are contained in the lingual branch of the complex trigeminal or fifth cranial nerve, making many synaptic connections with other neurones before finally being projected in the somesthetic (parietal) cortex in certain specific areas corresponding to positions of the body (Penfield and Rasmussen, 1950). The calibre size of the fibres from these so-called cutaneous receptors are in general smaller than those from the primary endings of muscle spindles so their conduction velocity is less (Murphy and Cameron, 1967).

How in fact the C.N.S. integrates all the sensory data arriving from such receptors is an extremely complex problem. However, some of the principles of neural circuits such as spatial summation at synaptic junctions, that were discussed earlier (see section 1.1.3.) suggest how this complex integration may be carried out.

It was seen earlier how each nerve cell in the nervous system receives impulses from many other cells. To take a simple example, suppose a group of neurones, A, receive impulses from say, free endings in the tongue tip and another group of neurones, B, receive impulses from Meissner corpuscles and other pressure receptors. Now an interneurone C, may receive in turn impulses from both group A and group B. If pressure is applied to the tongue tip, for example in the articulation of an alveolar stop, there will be an increased chance of firing occurring in neurones of group A and also in neurones of group B. Correspondingly, there will be increased chance of firing of interneurone C, because of the principle of spatial summation. We may thus reach a stage in which it could be inferred that activity of the interneurone C had been preceded by the presentation of a pressure stimulus to the tip of the tongue. Roberts (1966 : 63) gives a carefully reasoned account of this type of sensory discrimination.

Although this is, of course, an extremely over-simplified case, it may be possible, proceeding along similar lines, to theoretically map out pathways for physiological messages through the C. N. S. without relying at any stage on a one-to-one synapse with guaranteed transmission. These pathways may provide the physiological basis for the dynamic schema outlined in the previous section.

(b) The Proprioceptive System

The receptor organs contributing to vocal proprioceptive feedback are the muscle spindles, joint receptors and special endings called Golgi tendon organs.[1.]

Some aspects of the anatomy and physiology of muscle spindles have been outlined in section 1. 2. 2. It was seen how fusimotor activity, originating in the cortex, may play an important role in the myodynamic control of speech by setting a muscle reflexly to attain a specific length irrespective of local conditions of the muscle prevailing at any given time (Milner, 1967; MacNeilage, 1970). This system provides a very powerful means by which, for instance, a target configuration appropriate for an articulation such as [t] will be similar in two different environments such as [a t a] and [i t i], the actual differences being due to such factors as biomechanical constraints of the muscle (see below section 2), external forces acting on the muscle, mutual dependence on context, etc. This target configuration can thus be "set" without continuous motor commands being sent from the higher centres.

It was also suggested earlier, that firing of dynamic fusimotor fibres may have the effect of accelerating the contraction of the muscle as a whole and so assist in attaining, more rapidly, the target

1. Golgi tendon organs are receptors attached to the tendons of muscles. They respond to stretch on the tendon and their main purpose is probably to act as a sort of "safety valve" inhibiting the muscle when too much tension is exerted (Cooper, 1953). The tendon organs are probably only associated with those extrinsic tongue muscles directly attached to bones such as genioglossus and styloglossus.

configurations required for speech production (Öhman, 1967). This may happen, for instance, in the articulation of [a t a], where the tongue tip has to move a greater distance than for [i t i]. The time taken to move that greater distance, however, may not be longer because of dynamic fusimotor activity enhancing the appropriate extrafusal muscle firing.

It was also suggested earlier that the muscle spindle may play an important part in the reflex control of sensori-motor co-ordination. At an elementary level, reflex mechanisms can be regarded as basic stimulus-response activities. Stimulus in the form of stretch on the primary ending of the spindle causes a sensory discharge, which in turn causes the muscle to contract. Such mechanisms usually occur below the level of the cortex; they are, as Di Salvo (1961) notes, "very efficient and purposeful types of mechanisms, whereby lower levels of the C. N. S. may control functions which satisfy basic needs, leaving higher levels of the brain free to subserve behaviour of a more optional kind" (p. 336.)

Primary ending discharge probably plays an important part in providing information about muscle activity appropriate to the schemata of different articulations. Because of the direct monosynaptic pathway of the stretch-reflex loop and the fact that the impulses travel in large high conduction velocity fibres (Milner, 1967; Murphy and Cameron, 1967), this type of reflex mechanism is extremely fast acting. This rapidity may be important for sensori-motor control of speech where many different muscular activities take place every second.

In addition to the monosynaptic connections with the motoneurones of its muscle, the afferent fibres of the spindle also have polysynaptic connections with inhibitory and excitatory neurones (see section 1. 1. 3.), whereby the primary discharges not only help to activate the original muscle but to activate also synergistic muscles and inhibit the antagonists (Cooper, 1960). For an articulation such as [s], which requires finely graded control of both protagonist and antagonist muscles, the ratio of excitatory to inhibitory discharges is probably appropriately different.

It was mentioned above that the lingual nerve was responsible for providing tactile feedback from the anterior two-thirds of the tongue. It is by no means certain, however, that this nerve also provides the afferent innervation for the muscle spindles. Many investigators have suggested that the hypoglossal or twelfth cranial nerve, originally thought to be a purely motor nerve, has a sensory component along which impulses may travel from the spindles (Langworthy, 1924; Tarkhan, 1936; Cooper, 1953), although this opinion is not shared by all (e.g. Barron, 1936, thought that proprioceptive impulses from the tongue musculature are conducted by the lingual nerve, and Boyd, 1937, 1941, who concluded that the upper cervical nerves represent the only possible route for transmitting the proprioceptive impulses).

The fact that the autonomic component is more intimately mixed in cranial nerves makes the situation more confused. This, and other factors have severely hampered research into the sensory innervation of striated muscles in the territory of the cranial nerves (Hosokawa, 1961).

Considerations such as the innervation of sensory resources are important for designing experiments such as that outlined in Chapter 6.

1.3.2.1. Relative Importance of Different Types of Feedback in Speech Articulation.

Some investigators consider some types of feedback more important than others for the purposes of speech. Thus Fry (1957) states that, "by far the most important" feedback loop is the auditory, followed by kinesthetic (equivalent to proprioceptive in this context) feedback, with tactile feedback not seeming to play an important role at all. Various investigators since, however, have questioned the primacy of auditory feedback (e.g. Ringel and Steer, 1963; Ladefoged, 1967a).

The contribution of different types of sensory feedback will be discussed at greater length in Chapter 6. Suffice it to say here that rather than one type of feedback being more important than another for speech in general, it is probably more true to say that the exploitation of a given type of sensory feedback may vary in its importance, depending on the category of articulation involved.

1.3.3. Role of Sensory Resources in Anticipatory "Tuning in Advance".

Most of the exteroceptive feedback mechanisms discussed above operate after the muscular movements have been executed, for example, after the tongue touches the palate so activating the touch and pressure receptors in the oral mucosa concerned. It was seen earlier that for the nervous system to make full use of these different types of feedback mechanisms for speech, they must be efficient and fast-acting so that the speaker can continuously check the accuracy of the execution of the intended articulation. If any discrepancy occurs between the intended articulation and that which actually takes place, a monitoring system may correct the myodynamic performance. This probably happens for instance in the detection and correction of slips of the tongue (Laver, 1969).

This monitoring process may be facilitated by "priming in advance" not only the execution of motor actions but also the exteroceptive and proprioceptive "expectations" appropriate to these actions. As far as execution of motor actions is concerned, it is probable that for skilled, rapid muscular activities such as those required for speech, the neural correlates of these actions are "primed" or "pre-set" before the performance of the utterance begins (Lashley, 1951). Evidence of this can be found in anticipating tongue slips (Boomer and Laver, 1968; Laver, 1970) and in co-articulation phenomena (e.g. Öhman, 1966, 1967; Daniloff and Moll, 1968; MacNeilage and De Clerk, 1969). Lashley (1951), when speaking of the pre-set mechanism referred particularly to a certain type of fast accurate movement such as a whip-cracking motion with the hand, which, he claimed, could not be continuously monitored by sensory feedback from higher levels, because "the entire movement from initiation to completion requires less than the reaction time for tactile and kinesthetic stimulation. . . . " (p. 188). It is conceivable, however, that the neural correlates of sensory resources may be primed in advance or "tuned in" in much the same way as motor execution is. As Bernstein (1967) says, "proceeding with a determined program of operation, the central nervous system can, and indeed does, achieve anticipatory adaptation in terms of the tuning in advance of the arousal of all the sensory and motor elements which are employed. . ." (p. 162). Such anticipatory "tuning in advance" may not only facilitate the monitoring process after the event but may also be a means by which on-going sensory feedback control is facilitated.

These sophisticated neural mechanisms make it clear that the speech-system, once acquired by the child, is a remarkably skilled and efficient system. Some of the interrelationships between myodynamic control and feedback are examined in Chapter 6.

2. BIOMECHANICAL CONSTRAINTS ON MUSCULAR ACTIVITY

2.1. Introductory

In the preceding sections it was seen how muscles are innervated by peripheral neural elements and how sensory components probably contribute to the feedback control of motor activity. Most of the examples given considered the activity of a single muscle or single receptor organ. In reality, of course, any voluntary movement requires the co-ordinated activity of many different muscles, some being excited while others are inhibited, with probably thousands of receptor organs reporting on different aspects of the movement. It is important to realize that the actual mechanical activity of muscles, their contracting and relaxing, is automatic, in that their activity is entirely subject to neural signals; it is the C.N.S. that is responsible for the achievement of any voluntary movement. Thus the C.N.S. probably initiates a "plan" of the spatio-temporal aspects of the movement or series of movements, the details of which may be sorted out at a sub-cortical level, partly under the influence of sensory feedback from the organs concerned (see above section 1.3.3.).

Thus it is possible that contraction of a particular muscle will usually be accompanied by relative relaxation of its antagonist and vice versa, the extent of contraction being automatically determined by sensory feedback particularly proprioceptive feedback depending on prevailing conditions at any given time. Some articulations, however, particularly those requiring delicately controlled tongue configurations require a "balanced" contraction of both protagonist and antagonist muscles.

As muscular contraction is the basis of all speech movement it is important to consider biomechanical constraints of the muscle, which will affect the course of the activity. In the discussion on motor units it was seen how the time taken by a muscle to reach peak tension depends to some extent on the frequency at which the successive activations follow one another in each motor unit. It was also seen how the tension developed by a muscle depends on the number of motor units active at any given time. As the tension increases, more and more motor units are activated. It remains to be shown how the force developed by a muscle can also depend on inherent properties in the muscle itself.

2.2. Mechanics of Muscular Contraction

How does a voluntary muscle in fact produce the mechanical effect of contraction ? In the first section it was described how muscles consist of groups of fibres of varying shapes (section 1.1.4.1.). Recently, electron microscopy studies (e.g. by Huxley, 1958, 1965) have shown that striated muscle fibres themselves consist of longitudinally orientated myofibrils, orderly arranged to give the fibre an appearance of being divided into transverse bands (hence the name "striated" muscle). The striations divide the myofibrils into structural sub-units called sarcomeres within which there is an orderly array of two types of protein filaments, actin and myosin. Contraction of the muscle is caused by the sliding of actin filaments between myosin filaments while the lengths of the individual filaments remain unaltered. This mechanism also means that the filaments and so the fibres are not distorted during contraction. Where the myosin and actin filaments overlap, "cross-bridges" are formed

(Huxley, 1965); the tension developed by muscle fibres being related to the number of cross-bridges. Hypotheses concerning the means by which electrical potentials arriving via the motoneurones (see section 1.1.4.2.) are transformed into mechanical work in sliding filaments past each other, have been put forward by a number of investigators (e.g. Huxley, 1969) and will not be discussed here.

The main force-developing component of the muscle therefore corresponds to the actin/myosin complex described above, which may vary from muscle to muscle (Szent-Györgyi, 1953). The sarcome organization within a muscle will determine, for instance, the relationship between the load a muscle has to move and the maximal velocity at which the load can be moved. In general the lighter the duty, the swifter the movement (Gelfan, 1955; Cunningham, 1964). Most of the intrinsic muscles of the tongue need to have a steep tension/velocity curve to enable them to achieve the rapid movements involved in speech production.

2.3. General Problems of Co-ordination and Timing of Muscular Contractions

2.3.1. Biomechanical Constraints on Muscular Activity

In addition to the force-developing component of muscle (the actin/myosin complex) described in the previous section, there is also a series elasticity component, which will considerably influence the force a muscle can exert. The series elastic component consists of connective tissue within the muscle (accounting for about 15% of the total weight of the muscle) and tendons at the ends of muscles if they are attached to bones. As all muscles contain the elastic component, it must be taken into account in assessing the force developed by the muscle and the time taken to achieve peak tension. This is so because lengthening of the series elastic component increases the load on the contractile component so reducing the speed of shortening (Roberts, 1966).

In attempting to estimate the actual time course of events at the contractile machinery, Hill (1953) used the concept of "active state". The active state of a muscle may be regarded as the tension a muscle would develop at any instant if a direct measure of the contractile activity unmodified by series elasticity could be made. This useful model is reviewed in considerable detail by Davson (1964).

Other factors, such as the mass and inertia of the muscle, the work done against gravity and the mechanical properties of the imposed load must be taken into account in considering muscle activity. In the myodynamic control of speech therefore, it may be that factors such as the mass and inertia of the tongue muscles, properties of the imposed load, gravity, friction, etc., may result in "overshoot" or "undershoot" of the target positions irrespective of the fusimotor control mentioned earlier (cf. Tatham, 1969).

To sum up, therefore, the degree of force a muscle can develop and the time taken to achieve this force will depend on the following:

(i) elasticity of the muscle - tension/length and tension/velocity curves.

(ii) the number of motor units active at any one time.

(iii) the frequency of successive activations within motor units.

(iv) inherent mechanical properties of the muscle.

(v) mechanical properties of the imposed load.

2.3.2. Co-ordination of Muscle Groups

Mechanical activity in a muscle can lead to a number of different effects. These include:

(i) dynamic shortening of the muscle. In the case of the tongue muscles, contraction may move bones (e.g. the hyoid or mandible), or cause stretch on connecting muscles. This type of contraction is called isotonic contraction.

(ii) increased tension, where the muscle does not shorten. Tensions thus can prevent motion from occurring. Such contractions are called isometric.

(iii) lengthening. If the opposing force, for instance that exerted by an adjoining muscle is greater than the maximum contraction tension, the muscle is stretched or lengthened while actively contracting.

It can be seen from this that "contraction" has a special meaning referring to changes in mechanical properties. It is a rather unfortunate term because effect (iii) indicates that a muscle can be mechanically active without necessarily shortening.

When a number of muscles function together to achieve a movement of an organ, the various muscles are given different functional names, depending on their role in achieving the overall movement, such as prime movers (or protagonists), antagonists, fixation muscles and synergists. Each of these different roles will be considered in turn:

(a) Prime Movers or Protagonists

These are muscles primarily responsible for effecting the actual movements which occur. When the body of the tongue is moved forward in the mouth the protagonist is the posterior part of the genioglossus muscle (see below, section 3. 2. 2.). The movement is usually affected by a dynamic shortening of the muscles (i. e. an isotonic movement).

(b) Antagonists

These muscles may be inhibited from activity during contraction of the protagonists or they may actively contract to oppose the movement. Despite their name, the antagonists can also contract at the same time as the protagonists, contributing to a controlled movement by "paying out just as much as and no more than is required, thus securing guidance and precision." (Cunningham, 1964 : 268). The antagonistic capacity of various muscles in achieving delicately controlled tongue configurations such as is necessary in the production of [s] will be discussed at greater length in Chapter 5.

(c) Fixation Muscles

These provide a stable, fixed base from which other muscles can contract. In achieving many tongue movements, the infrahyoid muscles act as fixation muscles enabling the suprahyoid musculature to exert force on the relatively immobilized hyoid bone.

(d) Synergists

These are usually regarded as muscles assisting the protagonists in effecting a particular movement. The styloglossus can act as a synergist in assisting the intrinsic musculature of the tongue to raise the lateral borders of the tongue for the production of [s].

The key to voluntary movement lies in the co-ordinated activity of many muscles working together as a team. The problem of timing and co-ordination of muscles or groups of muscles becomes really acute when we consider the complex muscular adjustments that occur for instance in speech articulation.

2.3.3. Special Problems Relating to the Complexities of Timing and Sequence of Muscular Activities During Speech

Lenneberg (1967) estimates that the rate at which individual muscular events occur (throughout the speech apparatus) during articulation may be of an order of several hundred events every second. This means that speech probably exploits the co-ordinating systems in the C.N.S. more fully than almost any other volitional activity.

As an example of the problem of temporal integration, one can consider the activity of the tongue musculature in the production of a syllable as apparently simple as [s a t]. Each of the three segments requires a different target position and configuration of the tongue, achieved by balanced contractions involving both the extrinsic and intrinsic tongue muscles (see section 3). In addition, the position of the mandible and the hyoid bone must be set for each target configuration; this involves utilizing some of the tongue musculature, as well as the hyoid and mandibular musculature. In all, probably about thirty-five muscles are involved in achieving the tongue movements and configurations for each segment. When one considers that the three segments represent not three static postures of the vocal tract, but an almost continuously active sequence of events, where the muscles must contract dynamically in time, the extent of the temporal integration problem can be appreciated.

The next section discusses the anatomy of the muscles of the tongue, and some aspects of their physiology. The characteristic constraints on their physiological performance by the neuromuscular and biomechanical factors discussed in sections 1 and 2 should always be kept in mind.

3. DETAILED ANATOMY AND PHYSIOLOGY OF MUSCLES OF THE TONGUE AND ITS BONY ATTACHMENTS (HYOID AND MANDIBLE)

3.1. Introductory Remarks on the Muscles of the Tongue

3.1.1. Difficulties in Investigating the Anatomy and Physiology of the Tongue

The tongue consists mainly of muscle fibres and connective tissues arranged symmetrically on either side of a median fibrous septum and interlacing with one another in longitudinal, transverse and vertical directions. This intimate interlacing or interdigitation of the muscle fibres has probably accounted for the comparative lack of anatomical studies of the tongue musculature. It is extremely difficult and often quite impossible to separate completely the individual muscles even with the help of the dissecting microscope (Abd-el-Malek, 1939). The interdigitation of the fibres has also hampered attempts to record the electrical activities of individual muscles by electromyographic means (Mashiko, 1960). This is particularly so with surface electrodes on the tongue dorsum, where as was seen earlier (section 1.1.4.3.) records are extremely difficult to analyse in detail because they are composed of so many components all mixed up together (MacNeilage and Sholes, 1964). The use of hooked-wire electrodes has been limited to the intrinsic muscles and then only to the most superficial fibres (Bole and Lessler, 1966; Hirano and Smith, 1967).

A close review of the available anatomical literature on the tongue musculature, however, allows one to build up a fairly clear picture of the probable origin, course and insertion of each of the tongue muscles.

From this information it is possible to speculate on the functions of these muscles in moving the tongue for speech production.

3.1.2. Review of Literature on Tongue Musculature

The literature on the tongue musculature can be divided into three major sections :

(a) Anatomy of the tongue muscles.

(b) Physiology of tongue muscles.

(c) Experimental studies on tongue muscle activity.

(a) Anatomy of the Tongue

Most standard texts on anatomy (e.g. Gray, 1959; Cunningham, 1964) have a short section on the tongue musculature. The origin, course and insertion of the muscles are usually described. By far the most comprehensive description of the anatomy of the muscles, however, is in Abd-el-Malek's important paper "Observations on the Morphology of the Human Tongue" (1939). Not only does he describe fully the muscular system based on his own dissections and experimental work, but he also includes a good description of the fibrous septa of the tongue which is not usually included in standard text-books.

In view of the anatomical complexities of the tongue, it is hardly surprising that many conflicting statements occur in the literature, particularly concerning the extent and position of muscle fibre bundles in the intrinsic muscles. For instance, some investigators (e.g. Rouviere, 1943; Poirier and Charpy, 1901) deny the existence of verticalis fibres even after Hesse (1875) established their presence by a series of superb photographs of gross sagittal sections. Also, in connection with the median septum, Dabelow (1951), expressly denies that the septum is a fibrous dividing wall but asserts that it is a complicated linkage of the transversus muscles, thus disagreeing with Abd-el-Malek (1939).

In addition to the texts, there are a number of useful illustrations and photographs of tongue muscle sections. Hesse's (1875) photographs are probably still the most accurate serial sections to date and have been retained in a number of standard texts. Other illustrations such as those by Krause (1879), Pernkopf (1963) and Jamieson (1934) are extremely informative and accurate.

(b) Physiology of Tongue Muscles

Most of the general anatomy works (except Abd-e-Malek, 1939) devote some space to a discussion of the function of each muscle. This is usually restricted to a few general remarks and the physiology of the tongue muscles in speech articulation is only mentioned in passing. Some of the studies on the physiology of speech (e. g. Arnold, 1957; Van Riper and Irwin, 1958; Kaplan, 1960; Zemlin, 1964; Perkell, 1969) contain a section on the functions of individual muscles in speech production but here again, with the exception of Van Riper and Irwin (1958), the discussion consists usually of only a few general remarks.

(c) Experimental Studies on Tongue Muscle Activity

The experimental studies will be reviewed in Chapter 3, but a few general remarks are of relevance here. Most of the experimental studies using techniques such as palatography (e. g. Strong, 1956), cinefluorography (e. g. Perkell, 1969) and electromyography (e. g. Smith and Hirano, 1968) have included some interpretations of the experimental data in terms of functions of different muscles during speech. The most direct evidence, of course, comes from the electromyographic studies and these, as has already been observed, are limited almost entirely to those parts of the extrinsic muscles which show minimal interdigitation of fibres. Nevertheless, some of the investigations e. g. on the genioglossus (Smith and Hirano, 1968; Bole, 1965; Bole and Lessler, 1966) and on the mylohyoideus (Smith and Hirano, 1968) have produced interesting speculations on the activities of these muscles during speech. For instance, Bole and and Lessler (1966) found greatest activity recorded for the genioglossus muscle when the tongue was thrust forward meeting resistance against the teeth or alveolar ridge.

The activities of the intrinsic muscles of the tongue are still largely a matter of speculation. The following description of the anatomy and physiology of the tongue will attempt to provide a tentative working theoretical framework for experimental investigations of the physiology of tongue activity.

3.1.3. General Outline of the Anatomy of the Tongue

Before describing in detail the anatomy and physiology of the tongue musculature, a few general remarks about the structure of the tongue are necessary. The substance of the tongue is mainly muscle, with a mucous membrane covering (called the epithelium) papillary lamina propria, connective tissuesor septa, lingual glands and lymph nodules (see Fig. 2, section 1.2.2.). Anatomically, the organ can be divided into two parts - the oral and pharyngeal, usually separted by a V-shaped furrow on the upper surface of the dorsum (see Fig. 8). The oral part comprises two-thirds of the body of the tongue and is that part which is fully moveable in the mouth. It is loosely attached to the floor of the mouth at the front by a fold of mucous membrane called the lingual frenulum which is clearly visible when the tip is raised in a retroflex position.

The more fixed pharyngeal part of the tongue is anchored securely by muscle to the hyoid bone, the mandible and the styloid process. It lies just in front of the epiglottis, which is connected to it by the median glosso-epiglottic and the two lateral glosso-epiglottic folds (see Fig. 8).

The dorsum or upper surface of the tongue has a "velvety" appearance due to the presence of a large number of punctiform projections called papillae each containing a core of connective tissue and covered by the epithelium. Four types of lingual papillae have been identified on the anterior dorsal aspect of the tongue: filiform; fungiform; vallate and foliate papillae (Sognnaes, 1954). Within each of these papillae some form of nerve ending has been found (Dixon, 1962), the fungiform and vallate being particularly well

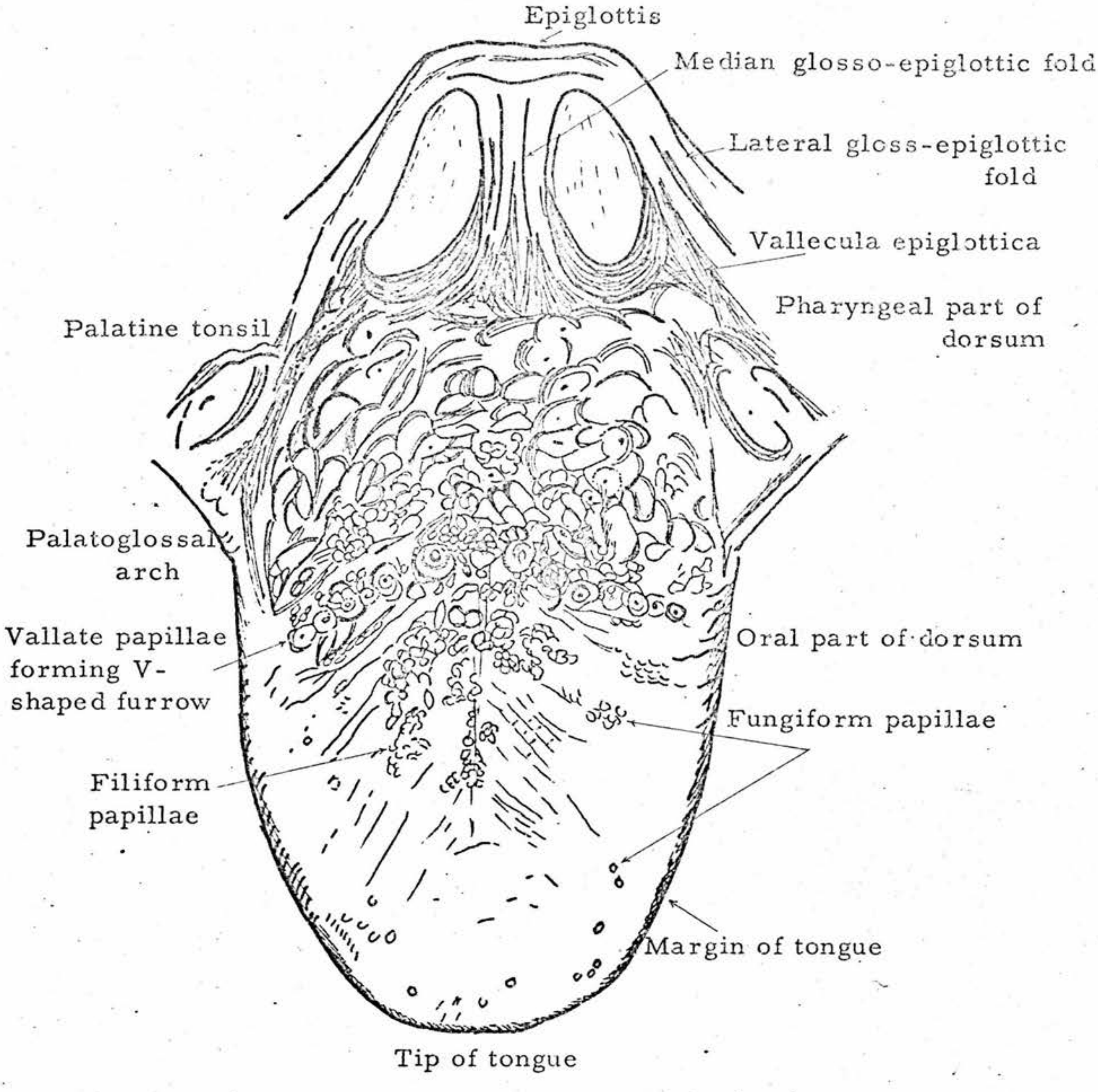


Fig. 8 View of the tongue dorsum and the palatine tonsils.
(from Cunningham, 1964 : 396)

endowed with taste buds. Grossman and Hattis (1967) have a good review of the histological work relating to the sensory endings in the papillary and sub-papillary tissues.

Immediately below the papillae projections is fatty tissue containing blood vessels, serous glands and nerve fibres. Because of the complex interlacing of nerve fibres in the connective tissue and sub-papillary region it is extremely difficult to isolate individual nerve endings.

Phoneticians have divided the dorsum into a number of divisions on a hypothecated functional basis. Pike (1943), for example, has "convenient arbitrary points of reference" which he calls *the tip* or *apex*, the *blade* and middle which are those parts directly beneath the hard palate, the *back* which is opposite the velum and the *root*, which is opposite the pharynx; adjectives like apical, laminal, etc. referring to points of articulation made with the relevant part of the tongue. But as Ladefoged (1967b), points out, neither the tongue nor the roof of the mouth can be conveniently divided into discrete sections, there being no satisfactory points of reference. It is useful, however, to retain a distinction between *tip* and *blade* articulations, a parameter which Ladefoged (1967b) calls *apicality*.

In addition to the epithelium, connective tissue of papillae and some of the ventral part of the tongue from the tip to the frenulum, there are a number of fibrous septa, which not only may separate some of the tongue muscles, but also serve as sites of attachment for them. These septa also contain in their substance the trunks of some lingual blood vessels and nerves.

The most important of these septa is the *median septum* (Abd-el-Malek, 1939) which is a fibrous longitudinal partition dividing the tongue into two halves and giving attachment to the median parts of the transversus muscles, one on either side (cf. Dabelow, 1951). It extends from the hyoid bone to the tip, being thickest and strongest in its middle portion. In addition to the fibrous septum, a number of investigators have isolated various other connective tissues in the substance of each half of the tongue (e.g. Abd-el-Malek, 1939).

The tongue muscles on either side of the median septum consist of an intrinsic and an extrinsic group. The extrinsic muscles have their attachments outside the tongue from the hyoid bone, the mandible and the styloid process and are thus capable of altering both the form of the organ and its position in the mouth. The intrinsic muscles, on the other hand,are located entirely within the tongue and so are capable, for the most part, of altering its form only. It is the intricate interactionsof these muscle groups that give the tongue its great mobility, making it capable of an almost infinite variety of positions and movements. This will become clearer during the discussion on the anatomy and physiology of the different muscles.

The tongue muscles are :

(1) Intrinsic Muscles
- (a) Superior longitudinalis
- (b) Inferior longitudinalis (paired)
- (c) Transversus (paired)
- (d) Verticalis (paired)

(2) Extrinsic Muscles
- (a) Genioglossus (paired)
- (b) Styloglossus (paired)
- (c) Palatoglossus (paired)
- (d) Hyoglossus (paired)

The palatoglossus can be considered as a muscle of the tongue or as a muscle of the palate (Zemlin, 1964). Here it will be treated as a muscle of the tongue.

Section 3.2. will describe for each of the eight tongue muscles the origin, course and insertion (where relevant), the motor innervation and possible function during speech articulation. The terms "origin" and "insertion" are convenient anatomical terms; origin referring to the more fixed attachment and insertion to the more mobile attachments of a muscle. It must be kept in mind, however, that often the fixed points are reversed in certain actions. Thus the anterior point of the mandible which sometimes serves as a fixed origin for the genioglossus muscle can also be moved by the same muscle for certain articulations depending on the state of other muscles.

The hyoid and mandibular muscle systems which are closely associated with the tongue musculature will be briefly discussed in sections 3.3. and 3.4. respectively. Attention will be focussed particularly on the functional properties of the different muscular systems. Thus in general, schematic diagrams, rather than graphic anatomical illustrations have been favoured.

3.2. Detailed Anatomy and Physiology of the Tongue Musculature

3.2.1. The Intrinsic Muscles

(a) Superior Longitudinalis Muscle

General description

The superior longitudinalis muscle lies directly beneath the lamina propria of the dorsum and extends from the root to the tip. It takes the form of a thin stratum of fibres at its anterior, posterior and lateral parts, but thickening to a bulky mass in the middle (see Fig. 9).

Origin

The posterior fibres in the form of a thin sheet are attached to the lamina propria of the mucous membrane close to the root. Some fibres can be traced back with difficulty to the epiglottis ligament and the hyoglossal membrane.

Course

The fibres pass in a longitudinal direction almost throughout the length of the tongue from root to apex. Most of the fibres lie immediately beneath the mucous membrane of the dorsum and are dorsal to the transversus and verticalis muscles.

Insertion

The anterior fibres flatten to a thin sheet and are attached to the lamina propria of the mucous membrane at the dorsal part of the apex. Laterally, the fibres spread out to join the longitudinal fibres of the styloglossus, hyoglossus and inferior longitudinalis musclesat the

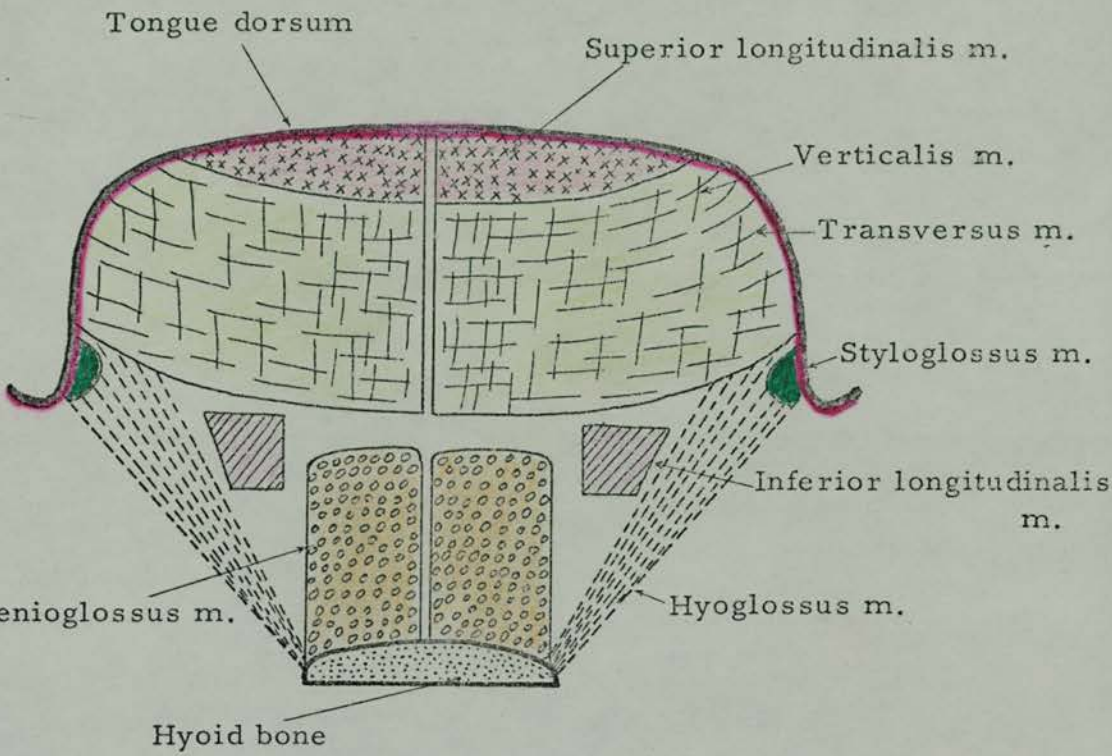


Fig. 9. Schematic diagram of a transverse section through the tongue showing the distribution of the intrinsic muscles of the tongue. The section is taken at the level of the first pre-molar teeth.

lateral borders of the tongue (see below).

Innervation

Motor innervation for the superior longitudinalis comes from the hypoglossal or 12th. cranial nerve.

Function

Upon contraction, the superior longitudinalis muscle has the general effect of shortening the tongue, perhaps also making the whole organ wider. In doing this it probably acts in synergism with the inferior longitudinalis muscle. It is probably the protagonist muscle in raising the tip for apical articulations occurring in the front part of the mouth. The lateral fibres may act in synergism with the styloglossus and perhaps also with the palatoglossus to keep the sides of the tongue raised during articulations requiring a grooved configuration (see below Chapter 5). The superficial fibres are probably protagonistic in retracting the tip for the articulation of retroflex consonants.

The superior longitudinalis muscle thus acts in conjunction with other intrinsic and extrinsic muscles in finely shaping the tongue for certain articulations.

(b) Inferior Longitudinalis Muscle

General description

The inferior longitudinalis muscle is a paired narrow muscle, oval in transverse cross-section, extending longitudinally throughout the length of the tongue between two septa in the lateral, vental part (see Fig. 9).

Origin

There are two attachments for this muscle; medial and lateral. The medial fibres decussate (see glossary) with the most lateral and ventral fibres of the genioglossus muscle from the anterior surface of the hyoid bone. The lateral fibres originate at the lateral part of the body of the hyoid bone and the root of the great cornu of the hyoid where they decussate with the medial fibres of the hyoglossus muscle.

Course and insertion

The muscle proceeds anteriorly towards the apex, partially rotating inferomedially. In the middle it blends with the anterior fibres of the genioglossus, hyoglossus and styloglossus in fixing onto the ventral part of the tip.

Innervation

Hypoglossal nerve.

Function

The general function of this muscle is probably to pull down and retract the tongue tip. In doing this, it can act in synergism with the anterior fibres of the genioglossus. In pulling down the tongue tip, the muscle acts as an antagonist to the elevators such as the superior longitudinalis and styloglossus. By depressing the tip and bulging the tongue upwards, the main part of the inferior longitudinalis can assist in the formation of certain back vowels and velar consonants.

With the hyoglossal muscle, the posterior fibres of the inferior longitudinalis may help to retract the main body of the tongue for the release of certain articulations. This action is only possible, of course, when the hyoid bone is fixed by the infra-hyoid musculature acting as fixators (see below section, 3.3.).

(c) Transversus Muscle

General description

The transversus muscle forms much of the muscular bulk of the tongue. The fibres are arranged in roughly horizontal layers which fan out laterally towards the tongue margins (see Fig. 9).

Origin

The muscle fibres take their origin from the median fibrous septum.

Course

From the median septum the fibres course laterally on either side of the tongue between the superior longitudinalis muscle dorsally and the genioglossus and inferior longitudinalis ventrally (see Fig. 9). Some of the superficial fibres travel in a dorso-lateral direction towards the tongue margins.

Insertion

The longer fibres of the muscle reach the lamina propria of mucous membrane of the side of the tongue, to which they have their lateral attachments. The majority of the fibres, however, are interrupted by neighbouring muscles such as the verticalis and genioglossus with which they decussate.

Innervation

The hypoglossal nerve.

Function

Upon contraction, the transverse fibres, particularly the more superficial fibres draw the edges of the tongue upwards, and by compressing the width of the tongue, may help to elongate it longitudinally. It thus acts mainly in synergism with other muscles such as styloglossus in forming a central groove in the tip and blade of the tongue for certain fricative articulation (see below Chapter 5). Together with the posterior genioglossus, it may help to push forward the tongue for frontal articulations such as alveolar stops and fricatives, when preceded for instance by a low back vowel.

It also probably acts as an antagonistic muscle to the verticalis in achieving finely graded tongue configurations necessary for certain complex articulations (see below Chapter 5).

(d) Verticalis Muscle

General description

The verticalis muscle consists of several bundles of short fibres placed more or less in a vertical direction. They decussate with the strata of the transversus muscle thus forming a considerable part of the central body of the tongue (see Fig. 9).

Origin

Most of the fibres originate in the mucosa of the dorsum. The greatest concentration of fibres occurs in the middle portion of the tongue immediately adjacent to the median septum.

Course and Insertion

The longer fibres sweep downwards from the mucous membrane of the dorsum on either side of the median septum to insert into the sub-mucous membrane on the inferior surface of the tongue. Some of the shorter fibres interdigitate with other muscles particularly the transversus muscle.

Innervation

Hypoglossal nerve.

Function

The general function of the muscle is to narrow the vertical cross section of the tongue and flatten it out sideways. The median fibres may act independently of the rest of the muscle in the formation of a grooved configuration. Synergistic contraction of the styloglossus, palatoglossus and transversus will contribute to this grooved configuration. In flattening the tongue, the muscle probably plays an important part in the production of certain front vowels. It also helps push the tongue laterally to maintain palatal contact for the closure phase in alveolar and palatal stops.

As with the other intrinsic muscles, the verticalis assists other muscles in achieving delicate alterations necessary for finely controlled tongue configurations.

3.2.2. The Extrinsic Muscles

(a) Genioglossus Muscle

General description

The genioglossus is a flat triangular shaped muscle which forms most of the substance of the central core of the tongue. (see Fig. 9)

Origin

The muscle takes its origin from a tendinous connection fastened to the superior mental spine on the posterior border of the mandibular symphysis (see below section 3.4.).

Course and insertion

The anterior fibres curve fan-like in an antero-dorsal direction to join the inferior longitudinalis, the hyoglossus and some fibres of the styloglossus at the tip (see Fig. 10). The posterior fibres travel horizontally and backwards to the anterior surface of the hyoid bone

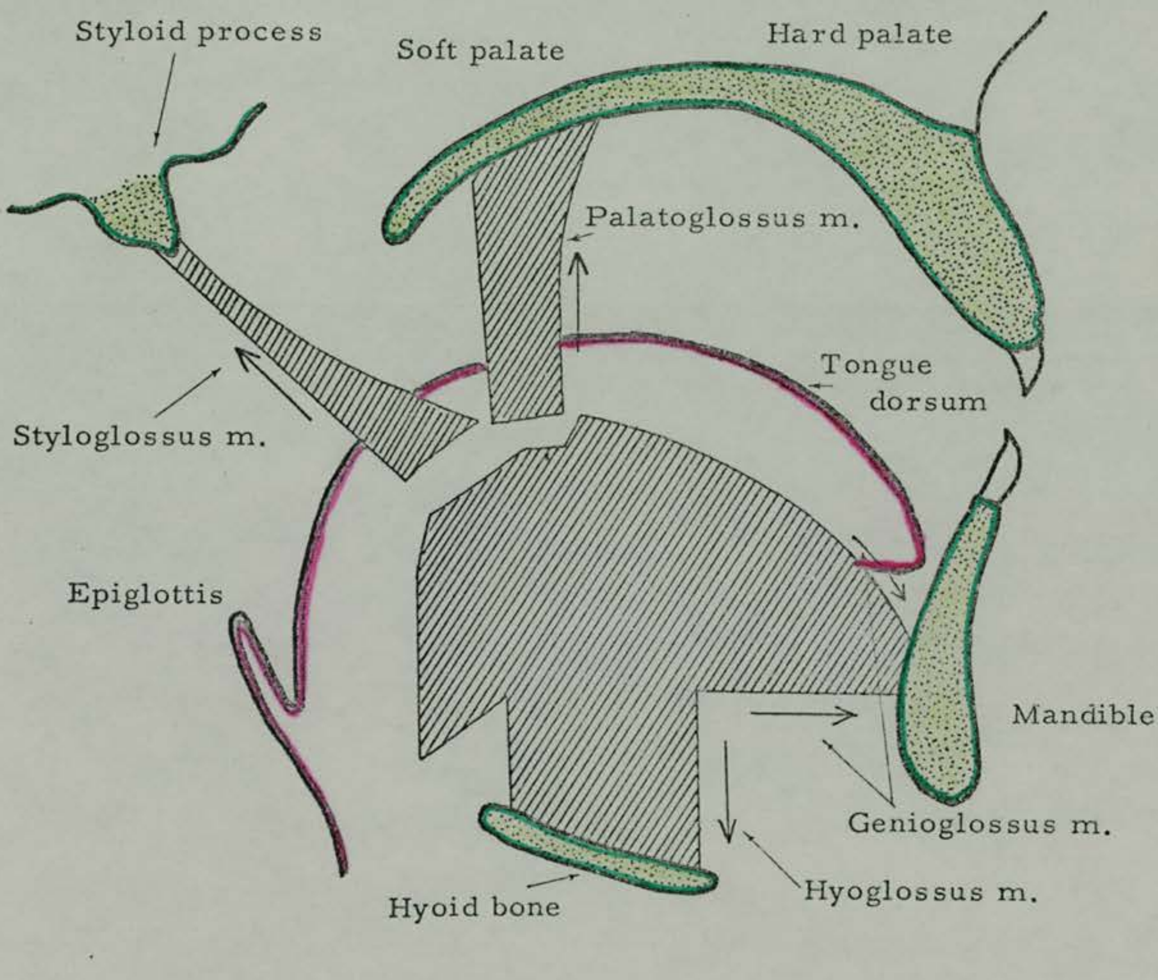


Fig. 10. Schematic diagram showing the four extrinsic muscles of the tongue and their external attachments. The arrows indicate possible directions of movement of the tongue when the muscles contract from fixed origins.

and interior surface of the base of the epiglottis. (Abd-el-Malek, 1939). Most of the intermediate fibres travel in a medio-lateral direction, where some decussate with the fibres from the opposite side and some with the superior longitudinalis and transversus muscles.

Innervation

The hypoglossal nerve.

Function

The anterior fibres contract to retract and depress the tip. Here it acts in synergism with other retractors of the tongue tip, for example in the release of alveolar stop consonants. The posterior fibres contract to draw the tongue forward in the mouth while the mandible remains fixed (see section 3.4.). As the posterior fibres are connected with the hyoid bone, any contraction from a fixed mandible will move the hyoid bone forward and up. This will result in the whole body of the tongue moving forward in the mouth. The posterior fibres are thus important for the production of most fronted consonants and also, with the help of intrinsic muscles for the formation of most vowels. Also with the help of elevators such as styloglossus and palatoglossus, the posterior fibres of the genioglossus will cause the tongue body to move upwards and forwards in the mouth. The intermediate fibres of the genioglossus act with the posterior fibres to draw the tongue forward and perhaps depress the middle part of the tongue.

Because the posterior and anterior fibres of the genioglossus independently serve different functions some investigators have suggested the genioglossus is really two different muscles (MacNeilage and Sholes, 1964).

(b) Styloglossus Muscle

General description

The paired styloglossus muscle is a flat, fan-shaped sheet of fibres which travels downwards towards the tongue from the styloid process of the temporal bone (see Fig. 10).

Origin

The muscle begins as a short slip of fibres arising from the anterior surface of the styloid process in front of the ear.

Course

The muscle begins to radiate just anterior to its origin. It courses downwards and anteriorly where it divides into two parts, a lower and upper part before it reaches the tongue.

Insertion

The lower fibres decussate with the lateral surface of the hyoglossus muscle. The upper fibres constitute the longer part and they travel laterally toward the tip where they interdigitate with the fibres of the inferior longitudinalis muscle. Some isolated fibres probably actually reach the tip.

Innervation

The hypoglossal nerve.

Function

The styloglossus is one of the main elevators of the tongue. Because its insertion is primarily along the edges of the tongue, contraction of its fibres may tend to raise the lateral margins so forming a cup-shaped configuration or sulcalization towards the back part of the tongue. It is the main antagonistic muscle of the anterior genioglossus and hyoglossus in pulling the body of the tongue up and back.

It thus contracts to a certain extent in the production of most speech sounds but is a protagonist in the formation of the closure for velar and post velar consonants and for the production of back vowels. To prevent sulcalization of the back part of the tongue during some articulations such as velar stops, the inferior longitudinalis probably acts as a synergistic muscle to the styloglossus.

(c) Palatoglossus Muscle

General description

The paired palatoglossus is frequently described as a depressor of the soft palate (e.g. Kaplan, 1960). It does, however, insert into the tongue so it can be regarded as one of the extrinsic tongue muscles. It is sometimes referred to as the glossopalatinus (Cunningham, 1927).

Origin

The fibres originate from the under surface of the soft palate above the glandular layer, where they spread out to interdigitate with those fibres from the opposite side. It forms the lowest muscular stratum of the soft palate.

Course and insertion

The fibres course downwards and laterally to insert into the sides of the tongue where they interdigitate with the intrinsic transversus fibres and the superficial fibres of the styloglossus and hyoglossus. As the palatoglossus fibres descend, they form the anterior pillars of the fauces in front of the tonsil (see Kaplan's (1960 : 190) reference to Diamond (1952) who believes the palatoglossus fibres form a sphincter through the body of the tongue).

Innervation

Probably the accessory nerve through the pharyngeal plexus (Kaplan, 1960).

Function

When the soft palate is fixed, the palatoglossus muscle can assist in raising the back part of the tongue. It thus acts here in synergism with the styloglossus muscle and in antagonism with the hyoglossus muscle. Together with the styloglossus and some intrinsic muscles, particularly the inferior longitudinalis it can help bulge the back of the tongue upwards for velar articulations. As the muscle inserts into the sides of the tongue it is possible that it contributes also to sulcalization of the back part of the tongue.

(d) Hyoglossus Muscle

General description

The hyoglossus muscle is the only muscle which functions primarily to lower the tongue. It is a paired, quadrilateral sheet of muscles coursing vertically into the tongue body from the hyoid bone (see Fig. 10).

Origin

Most of the fibres originate from the lateral part of the anterior surface of the body of the hyoid bone and also the whole extent of the greater cornu. The anterior fibres interdigitate at their origin with the superficial and deep fibres of the geniohyoideus ,one of the main elevators of the hyoid bone (see section 3. 3.).

Course

The most anterior fibres travel towards the tip between the inferior longitudinalis and genioglossus medially and the styloglossus, mylohyoideus (see section 3. 3.) and the submaxillary gland laterally (see Fig. 9). The posterior and middle fibres travel towards the root of the tongue.

Insertion

The anterior fibres attach to the mucous membrane of the tip. Most of the posterior and middle fibres interdigitate with the fibres of the styloglossus and the lateral part of the inferior longitudinalis. Some of the middle and posterior fibres blend with the fibres of the superior longitudinalis dorsally and the transversus and genioglossus ventrally.

A small bundle of muscle fibres which originates from the lesser cornu courses parallel with the hyoglossus and inserts into the intrinsic muscles on the sides of the tongue. This bundle has been considered part of the hyoglossus muscle, but some writers identify it as a separate muscle, the chondroglossus, (Cunningham, 1964; Zemlin, 1964). The fibres, however, are not always present, so they are not treated as a separate muscle in this description.

Innervation

The hypoglossal nerve.

Function

When the hyoid bone is fixed, the hyoglossus muscle acts as the primary depressor of the body of the tongue. The anterior fibres act with the anterior fibres of the genioglossus in retracting and lowering the tip for the release of certain articulations. The inferior longitudinalis also helps synergistically in this activity.

The posterior fibres are inserted into the lateral part of the body so contraction will tend to pull down on the sides of the tongue. These fibres thus act as the main antagonists for the styloglossus and palatoglossus muscles and contribute to the production of delicate surface adjustments needed for certain grooved fricatives (see Chapter 5).

It may also work in conjunction with the styloglossus in positioning the tongue body for high back vowels and also to a certain extent for low back vowels (see MacNeilage and Sholes, 1964).

The anterior fibres probably oppose the forward action of the posterior fibres of the genioglossus in achieving a balanced control of the tongue body for the production of most front vowels.

To sum up, therefore, the intrinsic muscles seem primarily responsible for altering the internal shape of the tongue while the extrinsic muscles,although often assisting the intrinsic muscles in achieving specific tongue configurations, are mainly responsible for moving the body of the tongue about in the mouth.

3.3. The Hyoid Musculature

3.3.1. Introductory Remarks : the Bony Attachments of the Tongue

As mentioned earlier, the tongue is attached by muscles to three bony structures - the hyoid bone ventrally, the mandible anteriorly and the styloid process of the temporal bone, posteriorly (see Fig. 10). The styloid process, being part of the skull can be regarded as a fixed attachment, whereas the hyoid bone and mandible are both moveable. Since both the hyoid and mandible are intimately connected to the tongue musculature, it follows therefore that any movement of these two structures will affect the position and sometimes the shape of the tongue itself. The hyoid bone and the mandible, together with their muscular attachments will now be discussed.

3.3.2. General Description of the Hyoid Bone and the Hyoid Musculature

The hyoid bone is a U-shaped bone lying almost horizontally in the anterior part of the neck just above the larynx (see Fig. 11). It is

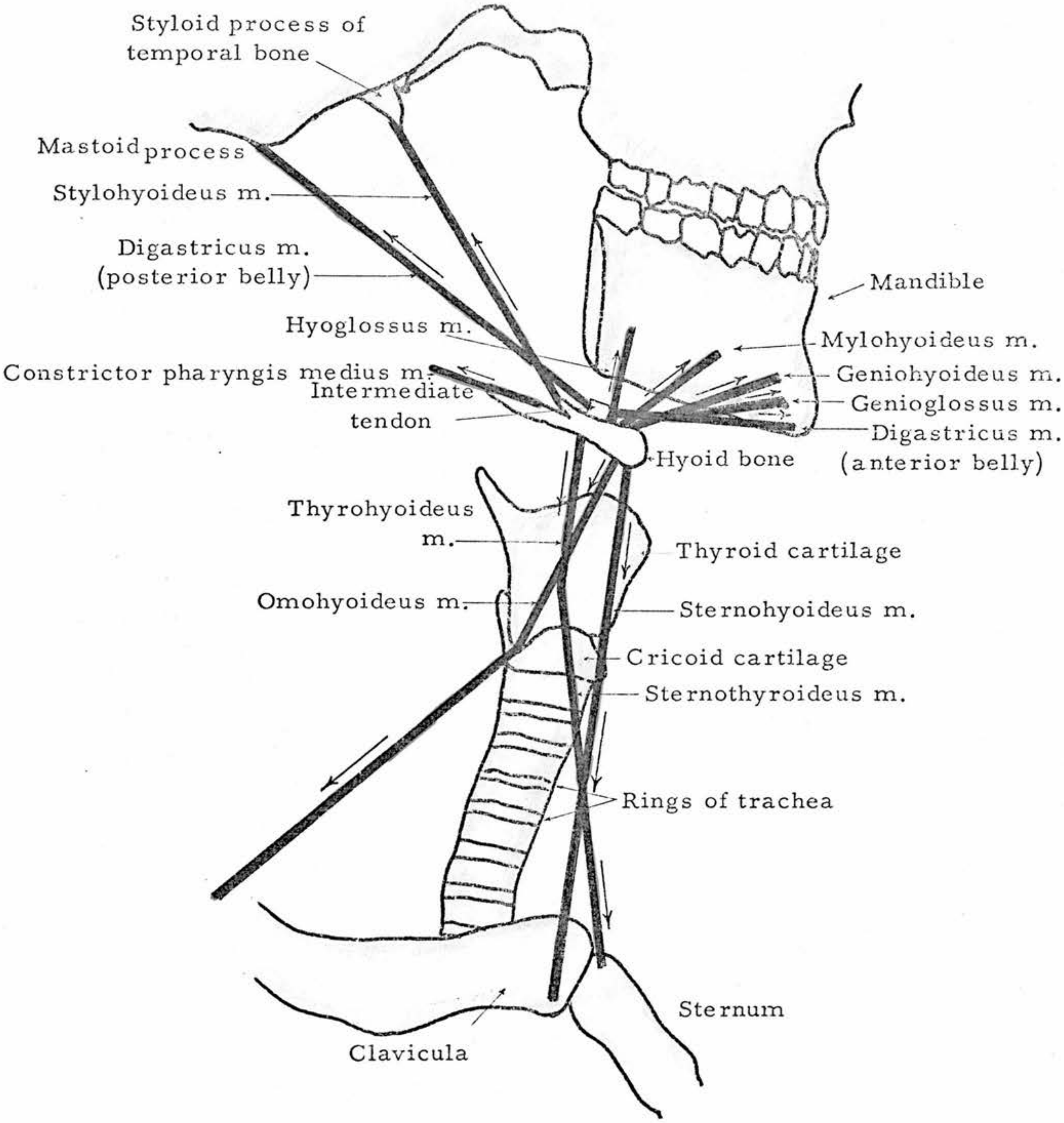


Fig. 11. Highly simplified schematic diagram showing some of the muscles of the hyoid. The arrows indicate (hypothesized) directions of movement of the hyoid bone when the muscles contract from fixed origins. (after Van Riper & Irwin, 1958)

unique in having no direct attachments to any other bone, but is held in position solely by muscles and ligaments. Muscles above the hyoid (the suprahyoid muscles) form a sling suspending the hyoid between the fixed styloid process and the anterior part of the mandible (see Fig. 11). Below the hyoid bone, another series of muscles (the infrahyoid muscles) connect the hyoid to the laryngeal cartilages and serve partly as antagonistic muscles to the suprahyoids.

The arrangement of the supra- and infrahyoid muscles is such that the hyoid bone can be moved in a number of different directions. Fig. 11 shows, schematically, the muscular connections and possible directions of movements from fixed origins. The most obvious movement is upwards or downwards but it can also be tilted forwards or backwards at the same time by different combinations of the two muscular systems.

The hyoid muscles are divided into two broad groups : (1) The Suprahyoids and (2) The Infrahyoids. The muscles of the hyoid are as follows :

(1) Suprahyoid Muscles
- (a) Hyoglossus muscle
- (b) Geniohyoideus muscle
- (c) Genioglossus muscle
- (d) Mylohyoideus muscle
- (e) Anterior Belly of Digastricus muscle
- (f) Posterior Belly of Digastricus muscle
- (g) Stylohyoideus muscle
- (h) Constrictor Pharyngis Medius muscle

(2) Infrahyoid Muscles
- (a) Thyrohyoideus muscle
- (b) Omohyoideus muscle
- (c) Sternohyoideus muscle

3.3.2.1. Suprahyoid Musculature

(a) Hyoglossus Muscle

The hyoglossus muscle has already been discussed with reference to the tongue musculature (see section 3.2.2. (d)). As a suprahyoid muscle, it probably acts in synergism with other elevators of the hyoid bone during most articulations especially in the production of alveolar and velar consonants. During these articulations, the tongue elevators such as the styloglossus and palatoglossus probably act as fixators for the hyoglossus providing, in the tongue, a relatively fixed base.

(b) Geniohyoideus Muscle

General description

The geniohyoideus muscle is a short cylindrical paired muscle lying close to the mid-line of the floor of the mouth.

Origin

The muscle fibres take their origin probably by means of a tendinous connection, from the anterior inner surface of the mandible, near the symphysis (see Fig. 12, section 3.4.).

Course and Insertion

The short fibres course downwards and posteriorly to gain insertion into the anterior body of the hyoid bone.

Innervation

Hypoglossal nerve.

Function

Together with the posterior fibres of the genioglossus, the anterior belly of the digastricus and the mylohyoideus muscles, the geniohyoideus helps to raise the hyoid upwards and forwards when the mandible is fixed (see Fig. 11). This action occurs in most articulations involving the raising of the tongue body. The genio-hyoideus may also act as antagonist to the thyrohyoideus muscle in tilting the hyoid backwards (see Fig. 11). This action may be important for the production of velar and uvular articulations (cf. Van Riper and Irwin, 1958 : 366).

(c) Genioglossus Muscle

This muscle has been described above in the tongue musculature.

When the mandible is fixed, the posterior fibres of the genioglossus can act in synergism with the mylohyoideus, the geniohyoideus and anterior belly of the digastricus in raising the hyoid.

(d) Mylohyoideus Muscle

General description

The mylohyoideus is a thin sheet of fibres forming most of the muscular floor of the mouth. It lies just ventral to the paired cylindrical fibres of the geniohyoideus.

Origin

The fibres arise from the mylohyoideus line running along the inner surface of the mandible back to a point almost adjacent to the second molars.

Course and insertion

The trough-like fibres course downwards and medially most of them decussating with their fellows from the opposite side. They combine at a tendinous raphe which extends from the mental symphysis of the mandible to the hyoid bone.

Innervation

The fibres are innervated by the mylohyoid branch of the inferior alveolar nerve, part of the trigeminal or fifth cranial nerve.

Function

The muscle acts in synergism with other suprahyoid muscles such as (a), (b), (c), and (e) in raising the hyoid and so the tongue, with the mandible fixed. The muscle also elevates the floor of the mouth, an activity which has some importance in swallowing. Although the muscle is significant in bringing the tongue forward for articulations such as the alveolar consonants [l], [t], [n], it also plays a large part in bulging the tongue up and back for velar articulations. (Hirano and Smith, 1967; Smith and Hirano, 1968). It probably acts here in synergism with suprahyoid muscles such as the posterior belly of the digastricus, the stylohyoideus and constrictor pharyngis medius.

(e) Anterior Belly of Digastricus Muscle

General description

The two bellies of the digastricus muscle, although functionally separate, are usually regarded as constituting the same muscle. Both bellies connect in a tendon near the hyoid bone (see Fig. 11).

Origin

The anterior belly arises in the inner surface of the mandible close to the origin of the geniohyoideus fibres.

Course and insertion

The fibres of the anterior belly course downwards and posteriorly to insert in the intermediate tendon attached to the body of the hyoid bone. There the fibres interdigitate with the fibres of the posterior belly.

Innervation

The digastricus muscle is served by the mylohyoid nerve, a derivative of the inferior alveolar branch of the trigeminal nerve.

Function

The main function of the anterior belly is to work in synergism with the other suprahyoid muscles in raising the hyoid. It may also contribute to the tilting movement mentioned in the description of the geniohyoideus muscle.

(f) Posterior Belly of Digastricus Muscle

Origin

The posterior belly of the digastricus arises in the mastoid process of the skull.

Course and insertion

The fibres travel downwards and anteriorly to interdigitate with those of the anterior belly at the intermediate tendon on the hyoid bone (see Fig. 11).

Innervation

Digastricus branch of the facial or seventh cranial nerve.

Function

Unlike the case of the anterior belly, contraction of the posterior fibres raises the hyoid upwards and posteriorly. This movement of the hyoid probably aids the upward movement of the tongue in velar articulations.

(g) Stylohyoideus Muscle

Origin

The fibres take their origin from the styloid process on the temporal bone close to the origin of the styloglossus fibres.

Course and insertion

The muscle travels downwards and anteriorly to fasten onto the greater cornu of the hyoid.

Innervation

Stylohyoid branch of the facial nerve.

Function

The main function of this elevator of the hyoid bone is to work in synergism with the posterior belly of the digastricus in drawing the hyoid upwards and backwards. The posterior movement is probably aided by the constrictor pharyngis medius and may be important for velar and uvular articulations. Because the fibres attach to the greater cornu of the hyoid, any contraction will tend to tilt the hyoid bone forward with the sternohyoideus and omohyoideus acting as fixators (see Fig. 11). This action may aid in bringing the tongue forward in the mouth for frontal articulations such as alveolar stops [l], [n] and inter-dental fricatives e.g. [θ].

(h) Constrictor Pharyngis Medius

General description

This muscle is mainly responsible for contracting the pharynx during swallowing, but it may also act as a weak elevator of the hyoid bone. The movement is more posterior than upwards however.

Origin

The fibres arise from the greater and lesser cornu of the hyoid.

Course and Insertion

From the hyoid bone the fibres run fan-wise around the pharynx to insert into the median raphe of the pharynx.

Innervation

The motor nerve supply is through the pharyngeal plexus into which passes the accessory nerve.

Function

The muscle probably acts in synergism with the posterior belly of the digastricus and the stylohyoideus in moving the hyoid upwards and posteriorly. The effect of this muscle on the movement of the hyoid is, however, probably only slight (Van Riper and Irwin, 1958).

3.3.2.2. Infrahyoid Muscles

In general, the three infrahyoid muscles act synergistically in drawing the hyoid and so also sometimes the larynx, downwards. In doing so, they help to retract and lower the tongue, thus assisting the hyoglossus muscle. Because the differential contraction of the infrahyoids may assist in the proper positioning of the hyoid bone for various articulatory positions, each will be discussed briefly.

(a) Thyrohyoideus Muscle

Origin and insertion

The thyrohyoideus muscle arises from the oblique line of the thyroid cartilage, passing over the thyrohyoid membrane to insert into the lower border of the body and adjacent parts of the greater cornu of the hyoid (see Fig. 11). It is a short quadrilateral muscle.

Innervation

The innervation of the muscle comes from the loop between the first and second cervical nerves.

Function

The thyrohyoideus acts in synergism with the other infrahyoid muscles in lowering the hyoid and so lowering the whole body of the tongue. With the hyoid fixed, however, the thyrohyoideus can raise the larynx which may be important for example in producing higher fundamental frequency.

Because of its insertion in the greater cornu, any contraction of the thyrohyoideus will tend to tilt the hyoid backwards. This may produce an appropriate position of the hyoid for the production of velar and uvular articulations (see Fig. 11).

(b) Sternohyoideus Muscle

Origin

The sternohyoideus muscle arises from the posterior surface of the manubrium sterni, from the posterior sternoclavicular ligament and from the medial end of the clavicle (see Cunningham, 1964).

Course and insertion

The muscle converges slightly with its fellow as it ascends to insert into the lower border of the body of the hyoid bone.

Innervation

Innervation is by the ansa cervicalis, the superior root of which runs with the hypoglossal (see Cunningham, 1964 : 288).

Function

The main function of the muscle is to depress the hyoid when the sternum is fixed. It also tends to tilt the front of the hyoid down. This probably happens for frontal articulations.

(c) Omohyoideus Muscle

Origin

The muscle has two bellies. The inferior arises from the upper border of the scapula as a narrow muscular band.

Course and insertion

The inferior belly passes in a forward, upward direction to insert in an intermediate tendon under cover of the sternocleidomastoideus muscle (see Cunningham, 1964). From this tendon, the superior belly courses vertically upward to insert into the lower border of the body of the hyoid bone (see Fig. 11).

Innervation

Same as for the sternohyoideus.

Function

The general function of the omohyoideus is similar to that of the sternohyoideus.

3.3.3. Summary of Hyoid Musculature

The movements of the hyoid and the muscles contributing to these movements can be summarized as follows :-

(1) The Suprahyoid Muscles

Hyoid movement : upwards

Hyoglossus muscle

Hyoid movement : upwards and forwards

Geniohyoideus muscle

Genioglossus muscle

Mylohyoideus muscle

Anterior belly of disgastricus muscle

Hyoid movement : upwards and backwards

Posterior belly of digastricus muscle

Stylohyoideus muscle

Constrictor pharyngis medius muscle

(2) The Infrahyoid Muscles

Hyoid movement : downward

Thyrohyoideus muscle

Omohyoideus muscle

Sternohyoideus muscle

3.4. Description of the Mandible and Mandibular Musculature

3.4.1. Description of the Mandible

The mandible is intimately connected to both the hyoid bone and the tongue musculature, so any movement it makes will necessarily alter the position and shape of the tongue. It is thus important for an understanding of lingual articulatory processes to see how and to what extent the mandible moves.

The body of the mandible is a roughly U-shaped arch when viewed from above (see Fig. 12). The closed end of the arch is situated anteriorly and constitutes the area of the chin. At both open ends of the U, bony extensions (rami) run upwards to join with the temporal bones in front of the ear.

3.4.2. Movements of the Mandible

From its joints on the temporal bones, the mandible is capable of the following movements :

(1) an upward movement
(2) a downward movement
(3) a protrusion movement
(4) a retraction movement
(5) an oblique, lateral movement

The muscles operate in functional groups to achieve these movements (see Fig. 13). The main muscles are as follows.

(1) Muscles of elevation :
  (a) internal pterygoideus muscle
  (b) masseter muscle
  (c) temporalis muscle
(2) Muscles of depression :
  (a) external pterygoideus muscle
  (b) geniohyoideus muscle
  (c) anterior belly of digastricus muscle
  (d) mylohyoideus muscle
  (e) posterior genioglossus muscle
(3) Muscles of protrusion
  (a) external pterygoideus muscle
  (b) internal pterygoideus muscle
(4) Muscles of retraction
  (a) temporalis muscle (posterior fibres)
  (b) mylohyoideus muscle
  (c) geniohyoideus muscle
  (d) anterior belly of digastricus muscle
  (e) posterior genioglossus muscle

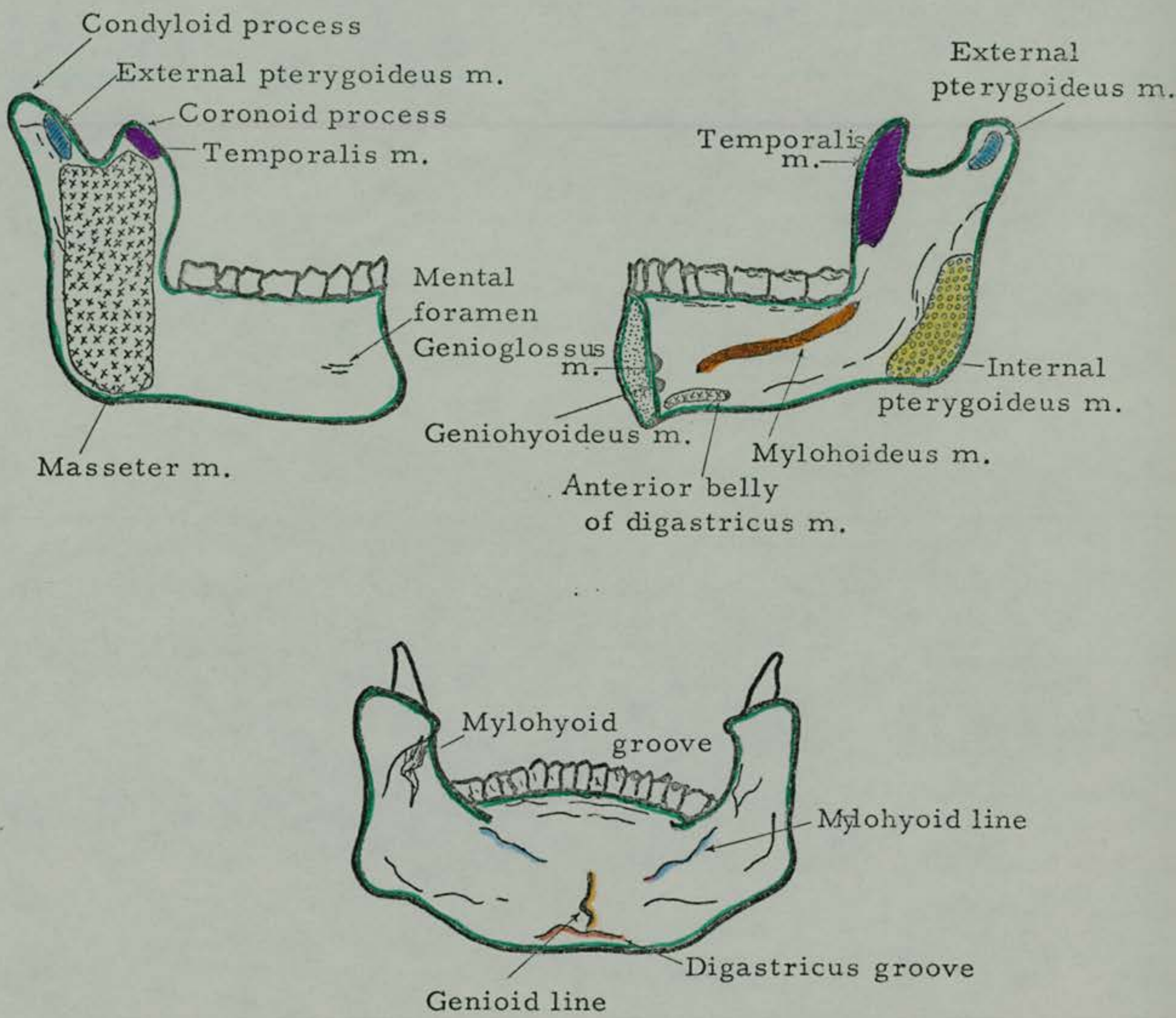


Fig. 12. Three views of the mandible showing the points of attachment of some of the mandibular muscles. (after Kaplan, 1960 and Cunningham, 1964)

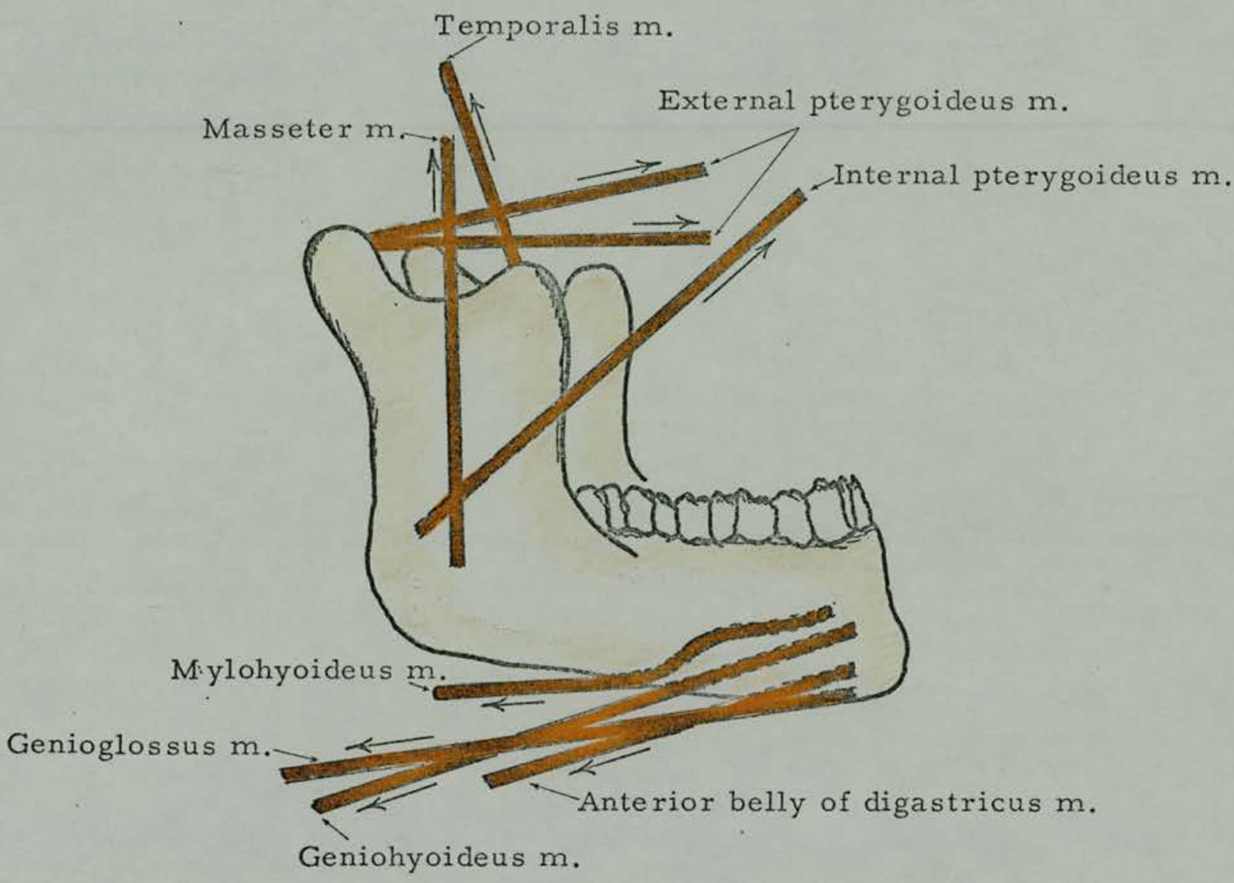


Fig. 13. Highly schematic diagram showing some of the mandibular muscles. The arrows indicate possible directions of movement of the mandible when the muscles contract from fixed origins.

(5) oblique lateral movement

(a) external pterygoideus muscle

(b) temporalis muscle (posterior fibres).

All of these movements are particularly important for chewing and grinding food. Some of the movements, however, are also important for some articulations. For instance, any raising of the mandible will also raise the hyoid bone, unless it is fixed by the infrahyoids and this movement will assist in the production, for instance, of high front vowels. Some investigators (e.g. Lindblom, 1967) have found a direct correlation between the degree of vowel opening and mandibular movement; the more open the vowel, the lower the jaw.

Most of the mandibular muscles have been described above under muscles of the tongue and hyoid. Some of the muscles, however, including the pterygoideus muscles, the masseter and the temporalis have not been mentioned so they will be described fully.

3.4.2.1. Muscles of Elevation

(a) The Internal Pterygoideus Muscle

General description

The three pairs of muscles constituting the mandibular elevator group all run vertically from the sides and undersurface of the skull to the mandible. As they contract the mandible is pulled up firmly against the maxilla (upper jaw). The internal pterygoideus muscle is a paired muscle lying on the medial surface of the mandibular ramus (see Fig. 12).

Origin

Most of the fibres originate in the pterygoid fossa of the sphenoid bone. The innermost fibres originate from the medial surface of the lateral pterygoid plate (see Fig. 14).

Course and insertion

The fibres run posteriorly and downwards to insert mainly at the rear of the ramus of the mandible (see Fig. 13). Many fibres insert in the medial surface of the mandible near its angle.

Innervation

Internal pterygoideus nerve branch of the mandibular nerve, part

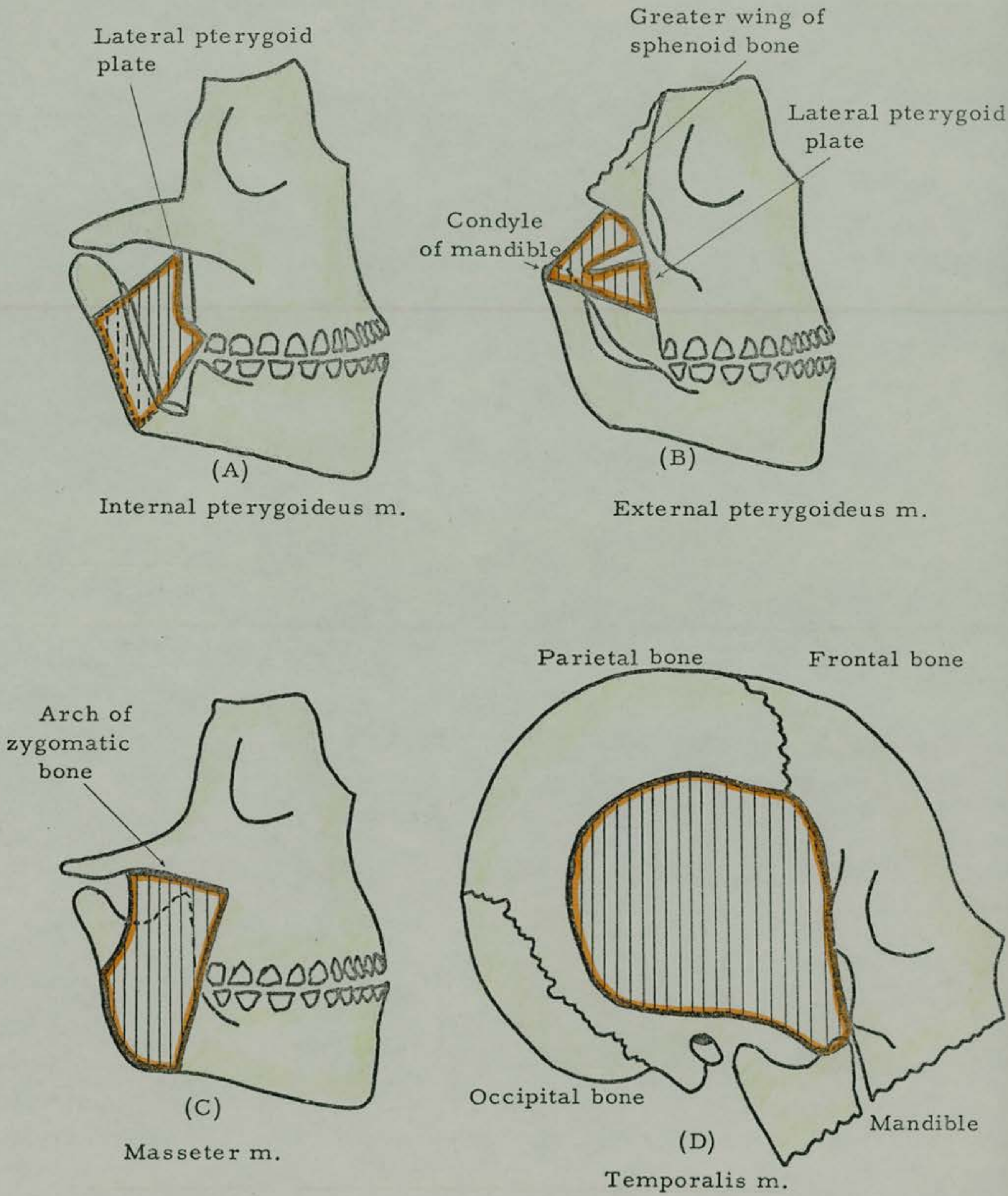


Fig. 14. Schematic diagrams illustrating four of the mandibular elevators and their attachments (from Van Riper and Irwin, 1958). In diagrams (A) and (B), part of the ramus and coronoid process of the mandible has been cut away.

of the trigeminal system.

Function

The main function of the muscle is to work in synergism with the masseter and temporalis in raising the mandible. It can also help to protrude the lower part of the mandible because of its slightly posterior course. The muscle acts in antagonism with the anterior suprahyoids in obtaining the balance of lip position necessary for production of fricatives e.g. [f], [v].

As mentioned earlier, this muscle and other mandibular elevators are used in the activity of chewing and grinding food. The grinding motion is helped by the external pterygoideus acting unilaterally.

(b) Masseter Muscle

General description

The masseter is the most superficial of the mandibular elevators. It is a thick, flat quadrilateral muscle lying on the outer surface of the ramus of the mandible (see Fig. 12).

Origin

The fibres originate from the zygomatic arch of the maxilla.

Course and insertion

The fibres course downward to insert into the angle and ramus of the mandible (see Fig. 14).

Innervation

Masseter branch of the mandibular nerve.

Function

The masseter muscle is usually regarded as the most powerful muscle of mastication (Kaplan, 1960). Not only does it act as a protagonist in closing the mandible but it also puts pressure on the molar region of the teeth. The deep fibres of the muscle can retract as well as elevate the mandible.

As mentioned above, the muscle may combine with the other elevators in raising the mandible and so the tongue in the production of alveolar articulations.

(c) Temporalis Muscle

General description

The third mandibular elevator is a large paired triangular sheet of fibres covering a large area on the side of the skull (see Fig. 14).

Origin

The fibres arise continuously from the temporal bone of the skull from an area that begins at the side of the forehead and extends to behind and above the external ear. This large area on the side of the skull is usually called the temporal fossa.

Course and insertion

The fibres course downwards and anteriorly to converge upon the coronoid process of the ramus.

Innervation

The temporalis branch of the mandibular nerve.

Function

The muscle acts in synergism with the masseter and internal pterygoideus in elevating the mandible (see Fig. 13). The posterior fibres help to retract the mandible. This retraction is assisted by the backward pull of the anterior belly of the digastricus, the geniohyoideus and the mylohyoideus. The infrahyoid musculature act as fixators in keeping the hyoid bone steady for this movement.

As with the other elevators, this muscle acts in antagonism to the mandibular depressors in maintaining the balanced position necessary for the production of some fricatives such as [f], [s] and most front vowels.

3.4.2.2. Muscles of Depression

(a) External Pterygoideus Muscle

General description

The external pterygoideus muscle is a thick triangular muscle located deep to the temporalis and coursing in a horizontal direction (see Fig. 13).

Origin

The fibres originate in two heads. The larger inferior head arises from the lateral pterygoid plate, and the smaller superior head arises from the greater wing of the sphenoid bone of the skull (Fig. 14).

Course

The two heads fuse as they pass posteriorly and horizontally in front of the temporomandibular joint (see Fig. 14).

Insertion

The fibres insert upon the condyloid process of the mandible and also upon the capsule and articular disc of the temporomandibular joint.

Innervation

The nerve supply is from the pterygoid branch of the mandibular nerve.

Function

As the fibres travel in a more or less horizontal direction the muscle acts more to protrude the mandible than to depress it. However, acting in synergism with the other depressors, it assists in the lowering movements. The muscle also assists in the oblique lateral movements important for grinding food, by functioning alternately with the posterior fibres of the temporalis muscle.

(b), (c), (d), (e). Anterior Suprahyoid Musculature

The anterior suprahyoid muscles, i.e. the geniohyoideus, the anterior belly of the digastricus, the mylohyoideus and posterior genioglossus have been described above under muscles of the hyoid. When acting in synergism with the infrahyoids, they can depress the mandible. It is only when the position of the mandible is fixed by the contraction of the mandibular elevators, that contraction of the suprahyoids will result in an upward, forward movement of the hyoid bone.

The mandibular depressors are important for the rapid lowering of the mandible, for instance, in facilitating the release of the closure for an alveolar stop.

3.4.2.3. Muscles of Protrusion

The primary protruder is the external pterygoideus mentioned above under muscles of depression. The internal pterygoideus and the superficial part of the masseter may act synergistically to assist the forward movement.

The protrusion movement may be important for instance in the articulation of labiodental fricatives such as [f] in some people's articulation and bilabial fricatives such as [ɸ].

3.4.2.4. Muscles of Retraction

The principal retracting muscles are the suprahyoid muscles mentioned above under the muscles of depression. In addition, the posterior fibres of the temporalis muscle,which run somewhat anteriorly as well as downward may assist in the retracting movement.

The movement is sometimes seen in the release phase of fricative [f] and in the production of low back vowels but the amount of retraction in speech is probably only slight.

3.4.2.5. Oblique Lateral Movement

The protagonist muscles for the lateral grinding movement of the mandible are the external pterygoideus and temporalis (posterior fibres). The movement is important for grinding and chewing food and is brought about by alternate protrusion and retraction of each side of the mandible with activity by the closing muscles. The two protagonist muscles function alternately and are assisted synergistically by all the mandibular muscles mentioned above.

The grinding and chewing movement is probably not of great importance in speech production (Van Riper and Irwin, 1958). However, some individuals, who have asymmetric jaw movements as idiosyncrasies may use this grinding movement in speech.

CHAPTER 3

INSTRUMENTAL INVESTIGATIONS OF LINGUAL ARTICULATION DURING SPEECH

INTRODUCTION

Although most phoneticians assert the prime importance of lingual articulation in speech production, relatively few instrumental investigations have been carried out in this field. There are probably a number of reasons for this :

(a) Rapidity of lingual movements

The anatomical structure of the tongue, with the intrinsic system providing delicate, rapid muscular adjustments superimposed upon gross positional movements by the extrinsic system, permit an almost infinite variety of lingual movements. Not only are these movements extremely varied, however, but they can be very rapid in speech: Stetson (1951 : 21) mentions 30 - 40 c.p.s. as a frequent rate of tongue tip movement during the production of a trill.

To record such rapid movements, fast-acting instrumental techniques with high frequency responses, have been necessary. Providing suitable instrumentation has proven to be a difficult problem in itself, which to a certain extent has hindered research on lingual articulation. Many of the older techniques used in experimental phonetics, such as registration of tongue contacts with the palate by means of pneumatic systems connected to a drum kymograph (see section 1.1.2 (d)) were severely hampered by mechanical difficulties, such as the relatively slow response time of the kymograph, which were inherent in the system. Much of the research done using these crude early techniques was consequently rather limited in scope.

In the last ten years, however, the situation has improved considerably. Many of the older techniques are being radically improved by the use of modern electronic equipment. Also with the advent today of sophisticated instrumentation, the phonetician can begin to gather quantitative information about the dynamics of complex lingual articulations, which previously, because of the speed and intricacy of their production, resisted successful investigation.

(b) Inaccessibility of the tongue

Another major difficulty in investigating lingual articulation is the organ's general inaccessibility. Most of the tongue except the most anterior oral part is entirely hidden from view during articulation, so is not accessible to direct, detailed observation from outside the mouth. It is possible, of course, to view much of the tongue's movements by lowering the mandible and observing through a mirror but normal articulation may then be interfered with, because of the anterior mandibular muscle attachments (see previous chapter).

Consequently, techniques such as cinephotography and direct visual observation, which have been used extensively in the investigation of lip and mandible activity during speech (see below section 1.1.2 (b)) have very limited application as far as research into lingual articulation is concerned. Photographing the tongue has been possible in one or two cases where part of the subject's cheek has been removed by surgery (see below section 1.1.2 (b)). But it seems most likely that the subjects in these circumstances had compensated for their "hole in the cheek" in various ways, so their speech was not typical of normal articulation.

(c) Radiation danger

Because of the inaccessibility of the tongue to direct observational techniques, some investigations have relied on radiography to penetrate the oral tissues concealing the tongue and so obtain information concerning lingual motions during speech. Any techniques, however, involving the use of x-rays have been severely limited by the inherent danger to body tissues of prolonged exposure to radiation. The radiation hazard has so limited the amount of data available for analysis, that it has been extremely difficult to extract any generalizations from most x-ray studies of lingual articulation.

It remains to be seen whether modern technology can eliminate the danger by minimizing the radiation dosage and thus allow full scale studies involving x-ray investigations of the tongue. Some progress has already been made (see below section 1.1.2 (a)) but as far as individual subjects are concerned, the danger level of radiation dosage is still an unknown factor.

(d) Delicacy of lingual articulation and sensitivity of the tongue

The difficulties and limitations involved in attempting to observe lingual articulation from outside the mouth by techniques such as radiography or photography have encouraged phoneticians to develop methods of investigating lingual movements from within the oral region. This has involved placing devices such as miniature multi-lens cameras, pneumatic bulbs, pressure transducers, etc. inside the mouth, usually attached to relatively fixed structures such as the hard palate, teeth or gums, but occasionally, as with surface electrodes for electromyography, on to the dorsum of the tongue itself. There are, however, a number of difficulties associated with the use of such intra-oral systems. Firstly, any foreign body introduced into the mouth is likely to interfere with articulation, both because of the delicacy of tongue movements and the organ's acute sensitivity to touch. The degree of interference will of course vary with the size of the instrument and its placement within the oral region. Some research workers, for instance, have successfully used pressure transducers situated on the gum in a space caused by a missing tooth. Convenient gaps of this type, however, rarely occur and the investigator is faced with the problem of placing the device where it will cause minimal interference with speech.

It seems likely also that interference will affect certain articulations more than others. Fricatives such as [s] for instance, because they require considerable delicacy of lingual movement and a high degree of tactile and proprioceptive feedback (see Chapter 5) are likely to be most affected by foreign bodies placed in the anterior part of the mouth.

(e) Complex anatomy of the tongue

Various attempts have been made to study lingual articulation by using electromyographic techniques to investigate the activity of individual muscles in the tongue. Such investigations, however, have been extremely limited. One of the main reasons for this is the complex anatomical structure of the tongue with the high degree of interdigitation of the fibres, making the electromyographic output data, particularly from surface electrodes, difficult to interpret. If needle or hooked-wire electrodes are used instead of surface electrodes, there is the added difficulty of causing possible damage to the intricate complex networks of nerve fibres, blood vessels and muscle fibres which constitute much of the dorsal part of the tongue. For a fuller discussion of electromyographic work on the tongue, see below section 1.3.1.

In addition, the complex anatomical structure of the tongue with its interconnecting muscle systems and prodigiously intricate neural networks has made it particularly difficult to provide comprehensive anatomical and physiological frameworksfor instrumental investigations of the tongue. Much research is still needed to unravel many of the complexities still surrounding lingual activity (see Chapter 2).

Since the late 19th century and the early part of this century, there have been quite a few instrumental techniques for examining lingual articulation. Some of these, for example Stetson's "exploratory bulbs", are little used today, but a review of such techniques not only highlights the difficulties involved in investigating lingual articulation but also provides valuable information useful for designing improved instrumentation. A review of the available techniques also illustrates the pressing need for more sophisticated, reliable and safe instrumentation for investigating the dynamics of lingual articulation.

In the study of lingual articulation there are three main areas of investigation. These are :

(1) Articulatory motions and configurations including the following: <u>static tongue postures</u>, for example during the closure phase for stops, nasals, fricatives and during the production of sustained vowels;

dynamic tongue movements, including timing of tongue contacts with the palate, etc.; pressure exerted by the tongue against the palate and teeth.

(2) Aerodynamics and acoustics of speech. Some instrumental investigations into the aerodynamics and acoustics of speech have provided indirect information on lingual articulation.

(3) Physiology of muscular movements, from studies of the electrical potentials accompanying muscular contractions.

This chapter is a short review of most of the available instrumental techniques used in investigating these three main areas.

1. INSTRUMENTAL TECHNIQUES FOR THE INVESTIGATION OF LINGUAL ARTICULATION

1.1. The Investigation of Articulatory Motions and Configurations

1.1.1. Static Lingual Postures Associated with Different Articulations.

(a) Static Radiographic Techniques

In 1895, Roentgen discovered x-rays and soon afterwards their application in phonetic research was realized. Scheier (1898) was probably one of the first to investigate vowel positions using x-rays, although the first full-scale study was not until Russell's The Vowel : Its Physiological Mechanism as Shown by X-Ray (1928). Apart from Russell, there have been quite a few static x-ray investigations, mainly of tongue positions during vowels (e.g. Eijkman, 1914; Jones, 1929; Parmenter and Treviño, 1932), the technique now being almost wholly supplanted by cinefluorographic techniques (see section 1.1.2(a)).

In static radiographic investigations, pictures are taken during the production of isolated sustained speech sounds, where the articulating structures are held immobile for the duration of exposure. Usually some radio-opaque form of outlining the tongue's dorsum, e.g. a thin silver chain or barium sulphate paint is used, and a tracing made from the x-ray photograph.

The limitations of this technique are immediately obvious. As

Moll (1960) indicated in his cineradiographic studies, "few if any characteristics of speech articulation appear to be constant with time during speech production" (p. 240). The two-dimensional representation of spatial relationship of the tongue to the palate also ignores the transverse shape of the tongue dorsum during articulation, although, if the central line of the tongue is outlined it is possible to measure the depth of a groove, for instance in the articulation of [s]. Added to this is, of course, the inherent danger of exposure to x-rays. So severe was this danger indeed, that many early investigations were abandoned because the subjects suffered x-ray burns (Russell, 1928).

One of the difficulties encountered in radiographic studies is obtaining clear outlines of soft tissues such as the tongue and soft palate. When muscles and tissues become superimposed, particularly in the soft palate and nasopharynx region, it becomes extremely difficult to interpret the photographs accurately.

A technique called laminagraphy overcomes this difficulty to a certain extent. Laminagraphy is a "body-sectioning" x-ray technique, permitting a radiographic reproduction of a predetermined plane or layer of body structure. It is thus possible to clearly visualize structures that would ordinarily be obscured by the superimposition of other calcified and soft tissue structures in conventional static x-rays. It has proved quite useful for frontal plane studies illustrating very convincingly, for instance, the asymmetrical configurations of the tongue during the articulation of a sound (Subtelny, 1956). Of course, the same limitations regarding radiation dosage apply to laminagraphic techniques as to conventional x-ray systems.

To sum up, therefore, static x-ray techniques can give a clear two-dimensional view of the outline of the tongue's dorsum in relation to the other oral structures during the production of isolated sounds. The disadvantages of the technique are exposure to radiation hazards, difficulties in interpretating data, static representations of isolated sustained speech sounds only, and normally no information concerning precise areas of tongue-palate contact.

(b) Mechanical Measuring Devices

A number of ingenious mechanical devices have been devised to provide outlines of the tongue during certain articulations. A necessary prerequisite for all these investigations is that the tongue be held quite immobile while the measurements are being taken. As in the case of static x-ray investigations, there is the limitation that such static postures are not representative of normal speech.

The mechanical measuring techniques include :

(i) Atkinson's Mouth Measurer

(ii) Tongue casting techniques

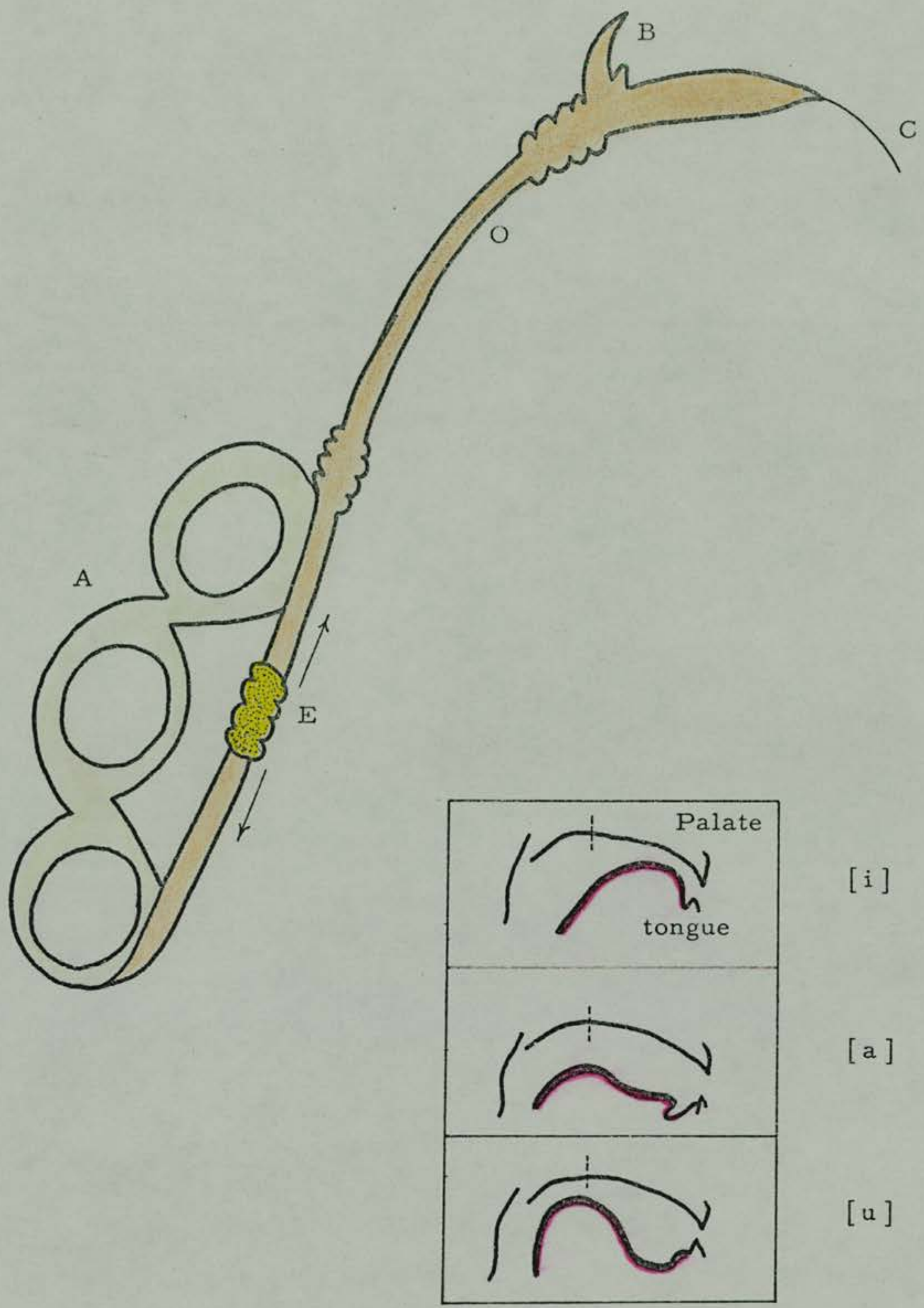
(iii) Plastographic and similar techniques

Much of the following discussion concerning mechanical techniques is derived from Keller's excellent monograph (Keller, 1961).

(i) Atkinson's mouth measurer

A sketch of the instrument is included in Fig. 15. A is the handle attached to a tube O. Inside O a wire C moves freely and can be pushed out to various lengths by means of E. B is a "tooth stop" which is adjustable and which, during use, is attached to the centre of the upper incisors. It is the end of wire C which gives the height of the tongue at a particular point since C can be adjusted while the sound is being produced,to a position just touching the tongue. After adjustment of C, the instrument is removed from the mouth and held against an outline diagram of a sagittal section of the palate and the point plotted in relation to the diagram (see Fig. 15).

The instrument was used by Atkinson (1899), the inventor, by Scripture (1902) and by Noel-Armfield (1931) to obtain diagrams, or stomatograms, as they were called, of various vowel articulations in different languages (see Fig. 15 for a stomatogram made by Scripture, 1902). It appears the instrument was fairly widely used in the early part of this century and various investigators testified to its usefulness (e.g. Jones, 1918; Sweet, 1913).



Three stomatograms
(from Scripture, 1902 : 332)

Fig. 15. Atkinson's Mouth Measurer (actual size) with three stomatograms obtained with the aid of the instrument.

In obtaining the tongue contours with the instrument, the usual procedure was to make a separate measurement for a number of repetitions of the same sound. However, because articulators are rarely in the same position for the production of a sound on two separate occasions, there were many discrepancies in the measurements obtained. Atkinson himself admits this is a limitation of the technique (Atkinson, 1899 : 502).

Another obvious limitation which arises from the distribution of sensory resources in the tongue is the fact that different areas of the tongue differ in their sensitivity to touch (see Chapter 2, section 1.2.2.1.); there is, for instance, less tactile acuity in the back part of the tongue. Thus, although it is permissible to rely on "just discernible touch" of the wire in the front part of the tongue, the tongue surface may have to be actually depressed by the wire before sensation is felt in the back part of the tongue.

Another limitation of the instrument is that the procedure is long and tedious and certainly would not encourage a full scale study. It of course gives no indication of tongue contact with the palate as well, so the information obtained from the technique is extremely limited. It does, however, avoid the radiation hazards of static x-rays while providing similar information on spatial representation of the tongue and the palate.

The instrument is little used today and is now something of a museum piece.

(ii) <u>Tongue casting techniques</u>

By using a suitable impression material (for example, alginate base dental material) it is possible to obtain a plaster cast of the front part of the tongue. Although fraught with difficulties, this method remains today the only way of obtaining a three-dimensional representation of tongue shape during articulation.

The usual technique is to insert dental impression material of a suitable consistency into the mouth during the production of a sound and hold the tongue immobile until the material hardens (Sapon, 1959).

In addition to the obvious danger of swallowing impression compound, especially if a soft palate cast is required, there are a number of difficulties associated with this technique. It is almost certain that the weight of the impression material would deform the tongue to a certain extent so that the resulting cast really bears an unreliable relation to the actual shape of the tongue during production of the sound. In addition, it is extremely difficult to hold the tongue immobile for any length of time. Various methods of mouth casting are described at length by Keller (1961). She came to the conclusion that problems of satisfactory casting techniques and interference of the material made this technique somewhat impractical.

Plaster casts of the palate may be extremely useful, however, for obtaining dimensions of a person's oral cavity. Examination of casts of a number of subjects also illustrates the considerable variations in the sizes and shapes of individuals' palates. The technique of mouth casting thus serves as a useful complement to techniques such as plastography and palatography (see below) which investigate contact of the tongue with the palate.

(iii) Plastographic techniques

Most of these techniques use some material which deforms during tongue contact. Erasmus Darwin (1806) describes in his notes to his poem, "The Temple of Nature", how he studied vowel sounds by placing rolls of tinfoil in his mouth and articulating the sounds in order to see where and how the tinfoil bent.

Another technique which Meyer called plastographic (Meyer, 1910), employed an artificial palate incorporating a line of fine leaden threads hanging vertically along the central line. After articulation, the shape which had been formed by the tongue pressing the leaden threads upwards was transcribed by a special method. In this way a profile of the tongue along the centre line was obtained.

The main disadvantage of these techniques is that they show only the maximum constriction that occurs during a whole utterance and give no indication of the timing of individual articulatory movements.

(c) Palatography

The techniques discussed so far give little indication of the exact location of tongue contact with the palate. This information is obtainable by the technique of palatography which has been perhaps the most widely used technique in studying tongue-palate contacts up to the present day.

There are two different methods of palatography, direct and indirect, both developed by dental surgeons in the latter part of the last century. The principle of direct[1] palatography was developed by J. Oakley Coles in 1872 out of an interest in helping his defective palate patients to speak correctly. He described the method as follows: "I took an impression of my upper jaw extending to the posterior wall of the pharynx, and thereby including the soft palate and fauces; also an impression of the lower jaw with the tongue in a state of repose. These I had engraved on one stone, with a drawing of the lips below. A number of these I had printed. Then my trial began. The mode I adopted at this stage was to make a mixture of gum and flour, and paint over the whole of the hard and soft palate and the surface of the teeth of my upper jaw. I then sharply articulated a letter. On the upper jaw where the tongue had come into contact, the flour was removed, and deposited on that part of the tongue which had touched it. These localities were at once faithfully transcribed on to the engraved plate with red paint." (Coles, 1872 : 112).

Coles's technique was most original, but as Abercrombie (1957 : 21) points out, his ignorance of phonetics prevented him from using it with profit. The technique was, however, used for linguistic research by a number of investigators including Grützner, Techmer and Rousselot for ten years or so after the appearance of Coles's paper.

1. The actual term "direct" was coined much later by Professor Abercrombie.

Soon after the appearance of Coles's technique, another dental surgeon, Norman W. Kingsley, described the technique of the artificial palate (Kingsley, 1879, 1880) and claimed to have produced excellent palatograms with it. This led to the emergence of the indirect or artificial palate method of palatography, which came to be used by experimental phoneticians in preference to the earlier direct method.

In the technique of indirect palatography, instead of painting the palate directly with some mixture, an artificial palate made of some substance such as vulcanite or acrylic, which fits onto the subject's palate, is painted with some material which will adhere to the tongue when contact is made. The artificial palate is then inserted into the mouth and, after the articulation of a sound, is immediately withdrawn. The "wipe-off" of the paint on the artificial palate, corresponding to areas of contact by the tongue, can then be examined at leisure. There were many immediate advantages of this method over the direct method; it was a cleaner, more efficient procedure and gave sharper outlines of tongue contact. The indirect method was used by most of the experimental phoneticians in the late 19th century and in the first half of this century, including Grützner (1879-83), Scripture (1902), Rousselot and Laclotte (1902), Gumpertz (1931), Kaiser (1936) and Stetson (Stetson, Hudgins and Moses, 1940), almost entirely superseding the direct method.

For the most part of this century, therefore, direct palatography was a neglected technique. Suddenly, however, there was a revival of interest in it in two different phonetics centres, Edinburgh (Abercrombie, 1957) and Uppsala (Witting, 1953). A new improved technique of direct palatography was described by Anthony (1954). The main improvement over the old system was that the subject's palate could now be photographed immediately after "wipe-off" by the tongue. These photographs or "photopalatograms", as Witting (1953) calls them, can provide a convenient permanent record of tongue contact with the palate associated with any particular sound.

The direct method in its improved form has a number of advantages over the indirect method. Firstly, it is possible with direct palatography to study the articulations of a large number of speakers without too much preparation. Indirect palatography, on the other hand, requires the manufacture of an artificial palate for each speaker and this is a lengthy skilled process, making the technique highly unsuitable for investigating a large number of speakers. Results from indirect palatographic investigations are thus usually of limited value as they are based on the study of a few individuals only.

Secondly, the direct method largely avoids the disadvantage of a foreign body (i.e. the artificial palate) in the mouth during speech, which possibly affects the action of some of the articulators.

In addition, direct palatography enables one to study a far wider range of articulations. The artificial palate is confined to the hard palate region, whereas the spraying mixture used in the direct method can cover both the soft palate and teeth as well, thus permitting the investigation of velar consonants and articulations involving contacts between the tongue and teeth.

Because of its general simplicity and convenience, the direct method is used extensively in many experimental phonetics laboratories today. It is particularly useful as a teaching aid for general phonetics students. As Abercrombie (1957 : 25) points out, "Articulatory movements which are not visible are not easy to grasp for beginners in phonetics, whose kinesthetic sense is usually still undeveloped for the tongue. Descriptions of these movements can be made more real and less purely theoretical by means of palatography (which must be active participation in palatography not just the exhibition of other peoples' palatograms)".

Although palatographic records are sometimes made of single isolated sounds involving tongue-palate contact, for instance [s], it is possible to make <u>word-palatograms</u> as well, (Firth, 1948a) which consist of a composite picture made up of a number of continually changing contacts, for instance [t i] where the lateral contact for the [i] becomes superimposed upon the contact for the [t]. The word-palatograms, in presenting features abstracted from a whole utterance regardless of seriality or timing illustrated, to a certain extent, Firth's prosodic theories (Firth, 1948b). Some of Firth's followers at the School of African and Oriental Studies in London used the technique of word-palatography extensively to investigate certain prosodic features in different languages (e.g. Henderson, 1952).

Whichever system of palatography is used, the articulatory data obtained is in the form of diagrams or photographs. Any diagram or photograph of the palate, however, is a two dimensional representation of information which was originally in three dimensions. As a result, palatograms often fail to convey important information concerning the depth of the palatal cavity and the slope of the alveolar ridge (Ladefoged, 1957). Without such information, it is extremely difficult to compare the articulations of different speakers.

Ladefoged (1957 : 766) suggests a "contour" system for providing a representation of palatal depth. This involves making a plaster cast of the mouth, which can be sawed along the mid-line, and also at regular horizontal intervals. A diagram of the sagittal section of the palate can be derived from the cast and a series of contour lines can be drawn in, similar to those used in cartography.

Even with the contour diagrams, it is rather difficult to compare the articulations of different speakers on the basis of palatograms. One of the sources of this difficulty lies in the problem of designing a scheme of reference, from which information such as whether a sound is post-palatal, can be extracted from the palatograms. Various attempts (e.g. by Firth, 1948a, and Jones, 1918) to solve this difficulty have been made basing the reference lines on the dentition, anatomical features of the palate, etc.

As a supplementary aid to radiography, which provides a sectional view of the tongue's outline, palatography, with its facility for providing a record of the areas of tongue-palate contact, can allow the phonetician to make some inferences about overall tongue shape in the articulation of certain sounds. The technique, however, is severely limited in that it can provide detailed information of isolated sounds or short sequences only and gives no temporal or sequential representations of lingual articulation. It is thus of limited use in some modern experimental studies which emphasize the timing and sequence of lingual movements during continuous speech. Nevertheless, some interesting findings concerning lingual articulation have resulted from palatographic investigations. These include:

(i) Auditorily identical sounds could be made by different tongue-palate contact-patterns. This was one of the reasons why an articulatory basis for vowel theory came to be distrusted by early experimenters (e.g. Russell, 1928).

(ii) Palatograms change with rate of articulation (Stetson, Hudgins and Moses, 1940).

(iii) Palatograms for repetitions of the "same" sound by the same speaker vary (Kaiser, 1941).

(iv) Stutterers' speech shows more variation than the speech of normal individuals (Gumpertz, 1931).

Closely connected to palatography and a useful complement to the technique is the method of recording the contact area on the tongue as well as the palate; usually this is called linguagraphy or glossography (Abercrombie, 1957). It is interesting to recall that Coles recorded the contact areas both on the palate and tongue, the mixture having adhered to the tongue after articulation. Very little work on this method seems to have been done in recent years. Probably the main difficulty has been finding a substance which will stick to the surface of the tongue and give a sharp outline of the wipe-off on the palate.

1.1.2. Dynamics of Lingual Articulation - Changing Spatial Representations of the Tongue and Timing of Articulatory Motions

(a) Cine X-Ray Techniques

As theoretical interests in experimental phonetics turn more towards physiological aspects of speech production, particularly the timing and serial ordering of articulatory movements, the sort of information from techniques such as cinefluorography becomes more and more necessary. Cinefluorography gives an x-ray representation of lingual articulation during continuous speech and as such is far more useful in providing quantitative data on articulatory events than is conventional static radiography (see section 1. 1. 1. (a)). As Moll (1960) points out, "Positions of the articulatory structures were shown to vary almost constantly, even during productions of isolated, sustained vowel sounds. This observation lends support to the notion that a single, cross-section-in-time analysis, such as that provided by single-exposure x-ray procedures, has serious limitations as a basis for description of the physiological characteristics of speech. If this much is granted, it would appear that almost every phase of speech which has been studied by single-exposure techniques should be re-studied using cinefluorographic procedures so that the dynamic changes in articulatory positions can be observed" (p. 240).

Cinefluorography differs slightly from more conventional cineradiographic techniques. Cineradiography involves photographing the series of x-ray images <u>directly</u> whereas cinefluorography is a more <u>indirect</u> method involving photographing a fluorescent screen onto which the x-ray images are projected. As the radiation dosage is lower in the latter technique it is now used almost exclusively for research purposes. (For a review of different techniques see Moll, 1960 and Subtelny, Pruzansky and Subtelny, 1957). A number of refinements have been added to the basic technique, for instance, a timing mechanism described by Bloom (1964) which synchronizes pulses derived from the cine-camera with the on-off projection of x-ray images.

High-speed cinefluorography is probably the best method for obtaining data concerning the dynamics of a wide variety of articulatory structures including the tongue, lips, mandible, soft palate and hyoid. The technique has therefore been used extensively in experimental phonetic research to investigate such phenomena as co-articulation features in speech production (e. g. Houde, 1968; Daniloff and Moll, 1968; Perkell, 1969).

Unfortunately, however, there are a number of limiting factors in x-ray high-speed motion picture studies: these include the radiation dosage problem (see earlier section 1. 1. 1(a)) and the difficulty in retrieving and processing necessary information from the motion picture film. The radiation hazard has meant that most detailed studies can be limited only to a very short stretch of speech, at most about a minute (see Perkell, 1969). Until the development of computer storage facilities, the processing of data was a severe problem because of the laborious nature of analysing high-speed film frame by frame (Fujimura, et. al., 1969).

The dosage problem has been overcome to some extent by image-intensifying techniques (Ter-Pogoisson, 1967), which limit the x.-ray exposure to only the moment and location at which it is effective in obtaining immediately useful data, and which detect and exploit the information carried by the x-ray protons by using a highly sensitive detector. However, there remain problems concerning the clarity of image (Fujimura, et. al., 1969). Another technique which lessens the dosage is an x-ray microbeam system described by Fujimura et. al. (1969), where a very fine ectron beam is pulsed onto a small area on the target. Such a system has only been possible because of advances in electron optics and the development of various kinds of electron-probe devices, including electron-bombardment machining devices, (Grivet, 1965).

Data-handling problems have been overcome to some extent by the use of computer techniques to process the data (Becker, et. al., 1964; Toriwaki, et. al., 1968; Fujimura, et. al., 1969) and this seems a promising avenue of research. Fujimura's system combines his x-ray microbeam system with an on-line computer control which he claims not only reduces the dosage but also facilitates data-handling (see Fujimura, et. al., 1969).

Thus, although advances are already being made in the field of high-speed cinefluorographic techniques to study speech articulation, the radiation hazard is still somewhat of an unknown factor and certainly presents some possible danger. It remains to be seen also whether promising new techniques such as Fujimura's will be suitable for analysing lingual articulation. So far experimental investigations have been concentrated on small confined regions of the body such as the vocal cords.

(b) Cinephotography

Studies involving direct photography of lingual movements during speech have been of two types; either photographing within the oral region by means of a miniature multi-lens camera (Brovchenko, 1954), or photographing from outside the oral region through a hole in the cheek, cut out for instance by surgery during cancer operations, etc. (Bogue and Fry, 1944).

Only extremely limited investigations have been carried out using these techniques. Brovchenko (1954) obtained crude data of tongue tip shape using a photogastrograph, but was hampered by the relatively large size of the instrument (31 mm. by 12.5mm.). Bogue and Fry (1944) used a subject who had had part of his right cheek removed, thus exposing to view the movements of the tongue during speech. The main disadvantage of this technique, however, is that the subject's speech cannot be completely normal; he must be making some compensations for the hole in the cheek.

(c) Proximity Sensing Techniques Using Capacitance Effects

A "tongue sensor" was developed by Hillix, Fry and Hershman (1965) to provide one of their six non-acoustic measures for a scheme for computer recognition of speech. Briefly, the tongue sensor element consisted of a capacitance probe divided into two active elements; one for the front half of the palate and one for the rear. The elements were small sheets of copper foil .001 inch thick driven by a 1 - Mc/sec. oscillator and shielded from the palate by a third sheet of copper foil large enough to shield both the lower elements. The energy radiated to the tongue was inversely proportional to the distance between the palate and tongue, so the instrument gave a direct but non-linear measure of the distance of the tongue from the palate. It was possible to measure tongue proximity to the palate as well as tongue-palate contact, thus giving better information about overall tongue shape than in other techniques, as for example, palatography.

The main disadvantage of the system in its present design is that no precise localization of tongue activity is possible. It gives only very general data in graphical form of the overall tongue proximity to the palate and it would be unsuitable for obtaining any detailed information of tongue shape and position. There are also considerable difficulties in calibrating the instrument (see Hillix, Fry and Hershman, 1965).

(d) Pneumatic Appliances Registering Localization and Timing of Lingual Contact on the Palate

Typical of these appliances used by early experimenters were the "tongue markers" used by Stetson (1951) and the "exploratory bulbs" of Scripture (1902).

These techniques relied on the use of the drum kymograph, which was designed to register changing air pressure. Stetson's tongue marker consisted of two rubber balloons filled with air and embedded in an artificial palate made of vulcanite in such a way that one was in the centre of the alveolar ridge and the other was at the back edge of the hard palate. Two tubes from the balloons passed out each corner of the mouth and were connected to the kymograph. During the articulation of the alveolar and velar stops, the balloons were pressed by the tongue, causing excursions of the kymograph scriber system (see Stetson, Hudgins and Moses, 1940). Scripture used exploratory bulbs mainly for the purpose of recording the pressure exerted by the tongue in different articulations. They were small rubber balloons inserted into the mouth by means of a handle and the pressure of contact recorded by means of a kymograph. They were, however, used by a number of investigators (e.g. Rousselot, 1897-1901; Laclotte, 1899; Josselyn, 1901; Jones, 1918; Stetson, 1928) to measure not only pressure but position and timing of tongue contacts as well. For example, Scripture (1902) mentions that Laclotte's (1899) records showed "that the tongue position during the consonant is lower in [b a] than in [b i], in [za] than in [z i]. the records show that the tongue takes, for the beginning of the work of articulation of the syllable, the position necessary for the vowel, and maintains it throughout the consonant and its explosion " (p. 372).

Many of the early investigators recognized the value of timing and pressure information and consequently these techniques enjoyed considerable popularity. As Scripture (1902), says, "The manner in which the tongue goes through the series of changes is certainly as characteristic of a speech movement as its position at any moment... Thus a diagram showing the point of the tongue pressed against the gums is described as a fronted alveolar articulation, and a [t] produced in this way is said to be frontal alveolar, whereas the chief characteristics of this [t] may lie in the manner in which the closure is made and released" (p. 325). The technique thus foreshadows later more sophisticated methods of recording dynamic lingual articulations (see later Chapter 4, electropalography).

These pneumatic systems are mechanically simple, but there are some disadvantages; the slow response time of the rubber tambours and drum kymograph makes accurate time measurements difficult; the presence of substantial foreign bodies in the mouth interferes with normal articulation and the limited number of bulbs or markers that could be placed in the mouth at one time permits only very general observations of tongue contact to be made.

The principle of measuring pressure with the aid of techniques such as the exploratory bulb system, is discussed at greater length in section 1.1.3.1.

(e) Geniohyoid Tambour

An indirect method of measuring tongue contact activity is of interest and can be briefly discussed here. Scripture (1902) describes an ingenious method of registering activity in the geniohyoideus muscle by means of a "geniohyoid tambour".

The tambour was held in place beneath the chin by straps around the chin and forehead. A knob resting under the chin moved by mechanical contraction of the geniohyoideus and the motion was transmitted by lever to the rubber top of the tambour. The variations in movement corresponding to tongue activity caused excursions in a kymograph scriber-system.

As was seen earlier in Chapter 2, section 3, a forward or upward movement of the tongue is usually accompanied by a tilting upward and forward of the hyoid bone, made possible by the contracting activity of the suprahyoid musculature including the geniohyoideus, the jaw remaining immobile by its fixator muscles. Thus one would expect, as Scripture found, geniohyoideus activity for [t, d] and a relaxation for velar sounds. He plotted degrees of elevation for the tongue associated with a number of Dutch consonants and vowels. It is extremely hypothetical, however, and at best over-simplified, that there is necessarily a one-to-one correspondence between mechanical contraction of the suprahyoids and tongue elevation. Elevation of the tongue may be due to action of other muscles than the geniohyoideus, for example posterior genioglossus and the intrinsic superior longitudinalis.

(f) Ultrasonic Techniques

The utilization of ultrasound waves to provide information on the configuration and motion of certain parts of the vocal tract has been discussed recently by Kelsey, Minifie and Hixon (1969). The basic principle of the technique is the reflection of ultrasonic energy whenever the high frequency sound beam passes from one medium into another medium having a different acoustic impedance. A sound beam source and transducer can thus be situated outside the oral region to register movements of certain oral structures. The technique has already been used to monitor lateral pharyngeal wall movement during speech and swallowing (Kelsey, Minifie and Hixon, 1969) and may well be used on tongue activity in the future. Although the system seems to offer a safe and reliable means of registering movement of articulating structures, it may prove difficult to localize accurately movement in different parts of the tongue.

A variation of the standard ultrasonic technique makes use of Doppler ultrasonic effects. The principle relies on the familiar Doppler frequency shift produced by a moving source and/or observer. A means of utilizing the Doppler effect to register velocity of the vocal cords is described by Kelsey, Minifie and Hixon (1969). It may be possible to adapt the technique to provide accurate information concerning the velocity of lingual movement. Ultrasonic techniques are still in the experimental stage as far as application to speech research is concerned. They seem to offer an extremely promising avenue for research in the future.

(g) Electropalatography

The need for data concerning aspects of dynamic lingual articulation has resulted in the development of electropalatography, which gives detailed information in real time about one particular aspect of lingual activity, namely, detailed information about the location and sequence of contacts that the tongue makes on the palate.

The sophisticated electronics of this system enable it to respond with accuracy to far more rapid articulatory movements than the mechanical devices mentioned above. It also avoids the risk of radiographic techniques. The system and its applications will be discussed at greater length in Chapter 4.

1.1.3. Pressure of Lingual Contacts with the Palate and Teeth

Research into lingual pressure has been carried out by both phoneticians and dental research workers. The techniques used by these investigators will be discussed briefly.

1.1.3.1. Research done by Phoneticians

This has been mainly confined to the exploratory bulb system used by Rousselot (1897-1901) and Scripture (1902), (see above section 1.1.1(d)).

Some research was carried out using the exploratory bulb system e.g. by Josselyn (1901) who studied pressure relationships in Italian sounds. The investigations, however, were severely limited by the slow response time of the mechanical apparatus (see section 1.1.1(d)). Because of the relatively large size of the bulbs also, it was impossible to put a number of bulbs in the mouth at the same time to study differential pressure exerted by the tongue at different points in the mouth.

No advances seem to have been made by phoneticians in this field since the early part of the century.

1.1.3.2. Research Done by Dental Research Workers

On the other hand, a great deal of research has been carried out by dental research workers in the field of lingual, and other soft-tissue pressures. These studies have been largely confined to soft tissue pressures on the dentition (e.g. Winders, 1958; Kydd, 1957; Gould and Picton, 1962; Proffit, Kydd, Wilskie and Taylor, 1964; Proffit, Palmer and Kydd, 1965; Proffit, Fogle, Heitlinger, Christiansen and McGlone, 1966) and on the palate (e.g. Proffit, McGlone and Christiansen, 1965; Luffingham, 1968).

Most of the investigations use some sort of pressure transducer either mounted intra-orally onto a tooth (e.g. Proffit, Kydd, Wilskie and Taylor, 1964) or extra-orally, connected to a pneumatic appliance similar to an exploratory bulb (e.g. Luffingham, 1968).

Pressure differences can be registered by deflection of miniature strain gauges or, as in Luffingham's system, by variations in the compressed air pressure within the pneumatic appliance. None of these systems, however, used a number of pressure transducing elements distributed throughout the palate and dentition, so were not suitable for investigating differential pressure at different points in the mouth during speech.

The possibility of adapting electropalatography to incorporate strain gauges to register differential pressure will be discussed more fully in Chapter 4. The research done by dental workers will be invaluable in providing information on the mechanical and calibration problems involved in pressure transducing.

1.2. The Investigation of the Acoustics and Aerodynamics of Speech

1.2.1. Acoustics of Speech

Instruments such as the sound spectrograph can provide indirect data on certain aspects of lingual articulation. Because movement of the tongue alters the shape of the oral cavity, the corresponding acoustic output will be changed. Stevens and House (1955) made a number of measurements from x-rays of certain parameters including distance from the glottis to the point of greatest constriction (normally caused by the tongue) and the radius of the oral cavity tube at the point of greatest constriction, and correlated these measurements with formant values measured from the spectrograph. They found some correlation between the physiological parameters and formant values; for example F2 increases as the point of construction moves forward from the glottis and the mouth opening increases. Many other investigators have attempted physiological interpretations of acoustic data from the spectrograph (e.g. Delattre, 1951, 1969; Fant, 1962; Lindblom, 1963; Öhman, 1965, 1966).

The spectrograph will also provide indirect measurements of timing of lingual articulation, particularly during the production of different types of speech sounds including stops, fricatives and vowels. Each of the speech categories has a characteristic spectrum, and details of the articulatory movements, for example, the closure and release phases of stops can be measured. Differences in place of articulation can also be perceived by means of the influence exercised on the formants, particularly the second formant, of the adjoining vowels.

Thus one can investigate, indirectly, three aspects of lingual articulation with the aid of acoustic data :

(i) timing of articulatory movements
(ii) manner of articulation
(iii) place of articulation (crude data only).

It is difficult to posit any one-to-one relationship between details of lingual articulation and acoustic spectra.

1.2.2. Aerodynamics of Speech

As was mentioned earlier, lingual articulatory patterns are related to the acoustics of the speech wave form and the aerodynamics of air flowing through the oral cavity. In the previous section it was seen how acoustic data from the spectrograph can provide some indirect information concerning lingual activity. Similarly, from a knowledge of volume and rate of air flow through the mouth and of pressure drop across the constriction between the tongue and the upper surface of the vocal tract, it is possible to calculate the timing of tongue movements and degree of constriction (see Scully, 1969). Warren and Du Bois (1964) discuss an extension of the Hydrokinetic Equation to calculate orifice area from a knowledge of volume flow rate of air, pressure drop across the orifice, density of air and a correction factor "k".

A number of instruments provide air flow data. These include the pneumotachograph (Isshiki and Ringel, 1964; Klatt, Stevens and Mead, 1966) and the electro-aerometer, designed by Sv. Smith and B. Frøkjaer-Jensen. The electro-aerometer is a far more sophisticated instrument than the old drum kymograph, which was discussed in section 1.1.1. The aerometer has a better frequency response than the drum kymograph and so can follow very rapid events more accurately. An oral pressure tube leading to a manometer, to give data on air pressure, can be used in conjunction with the electro-aerometer (Scully, 1969).

Aerodynamic data can thus be used to investigate different aspects of lingual articulation including :

(i) timing of lingual movements

(ii) closeness of the constriction caused by the tongue and thus quantitative and qualitative information on manner of articulation,

(iii) orifice area, i.e. area of constriction by the tongue, etc. from hydrokinetic equations.

1.3. Electrical Activities of Individual Muscles

1.3.1. Electromyography

In Chapter 2, electromyography was mentioned as a possible research tool in investigating the complex physiology of lingual activity. If one can obtain information concerning the electrical potentials associated with muscular contraction, one can infer something about the neuromuscular commands during co-ordinated activity. Before any research of this type is useful, however, one must formulate rigorous hypotheses concerning the physiology of muscular movements, particularly the co-ordination and group activities of muscles (see Chapter 2, section 2.3).

As was indicated earlier, the problems of co-ordination are particularly acute in the lingual musculature, with its complex muscle systems and extensive interdigitation of fibres. Thus electromyographic research on the tongue up till now has been rather limited and confined mainly to surface electrode studies on the intrinsic muscles (e.g. MacNeilage and Sholes, 1964) and hooked-wire and needle electrode studies on some of the extrinsic muscles including the genioglossus (Bole and Lessler, 1966) and mylohyoideus and geniohyoideus (Hirano and Smith, 1967). Some of the difficulties involved in interpreting EMG data from these muscles were discussed in Chapter 2 and in the introduction to this chapter.

There are, however, a number of more fundamental problems involved in electromyographic investigations. Most of these problems are related to the anatomy and physiology of the lingual musculature.

The aim of electromyography is usually to correlate quantitatively the EMG output with mechanical functions of the muscle, such as degree of tension and work performed by the muscle. This is possible when the muscle is maintained at a fixed length, i.e. when it is in isometric contraction (see Chapter 2, section 2); here there is usually a direct correlation between the degree of tension and the EMG tracing. However, the conditions of the experiment must remain absolutely constant with regard to the placement of recording electrodes and the physiological state of the muscle. As was indicated in the discussion on motor units (see Chapter 2, section 1.1.4.3), because of the uneven distribution of the units within the muscle, EMG tracings may differ quite considerably at different points in the muscle. Also it seems that muscular fatigue causes spurious

EMG readings. Edwards and Lippold (1956) showed the relationship between EMG and isometric tension changes during fatigue. One reason for this may be that motor unit firing becomes more synchronized during fatiguing work resulting in a misleadingly high EMG amplitude (Ralston, 1961). Thus readings taken during repetition of a number of utterances may be invalidated due to the effect of possible muscular fatigue.

Again, the precise effect of the muscle spindle and tendon organ discharge during changes in length (see Chapter 2, section 1.2.2.) is a little uncertain at present as far as the lingual musculature is concerned. Although there seems to be a direct relationship between tension and EMG tracing when the muscle is kept at a fixed length, under rapid changes of length there seems to be a complete lack of correlation between tension and EMG readings (Ralston, 1961). Much more precise information is required about the feedback effect of proprioceptors on neural commands for motor unit firing during rapid changes in muscle length before EMG tracings can be interpreted accurately.

2. SUMMARY

As was indicated in the introduction to this chapter, information about the complex physiology of tongue-movements is particularly valuable to phoneticians. However, a review of the available instrumental techniques to investigate different aspects of lingual articulation, shows there are very few techniques that can give any really useful information for experimental purposes. As interest in experimental phonetics is today mainly concentrated on dynamics of articulatory processes, including the timing and sequence of tongue movements during speech, those techniques which investigate static postures of the tongue are of very limited application. Of those techniques that investigate the dynamics of lingual articulation, cinefluorography and electromyography have seemed the most promising but there are many severe limitations to their use as was indicated above. Clearly there is a pressing need to develop more suitable instrumentation. This was the main reason for the development of the technique of electropalatography in the Phonetics Laboratory in Edinburgh. The following chapter describes in detail this technique.

CHAPTER 4

THE DEVELOPMENT OF ELECTROPALATOGRAPHY

INTRODUCTION

As we saw in the previous chapter there is at present a relative lack of suitable techniques for obtaining detailed information on temporal and sequential aspects of lingual articulation. This has encouraged, to a large extent, the development of electropalatography, a technique which aims primarily to provide a real-time display of the location and timing of tongue contacts with the palate during continuous speech.

Although the technique was developed mainly for use in experimental phonetic research, as the work progressed it became apparent that electropalatography might have other important practical applications, for example in the fields of education of the deaf and in speech pathology. It is not the intention of this thesis to explore thoroughly the application of the technique outside phonetic research, so discussion on these matters will be confined to a brief note at the end of this chapter.

The first part of this chapter will review a number of different techniques of electropalatography, most of which are still in the experimental stages. The second part of the chapter will describe in detail the development of the Edinburgh system of electropalatography, its limitations, and proposals for future modifications.

1. REVIEW OF AVAILABLE TECHNIQUES OF ELECTROPALATOGRAPHY

As suggested in Chapter 3, the forerunners of electropalatography were not only conventional static palatography providing information on areas of tongue-palate contacts, but also various pneumatic appliances, for example, the tongue markers described by Scripture (1902), to provide timing information on tongue contacts with the palate. Electropalatography, in providing detailed information on both the areas of tongue-palate contact and the timing of contacts as well, can be regarded as a combination of the principles of those two basic techniques.

A number of different systems of electropalatography have been developed over the last few years and some of these have been used for phonetic research purposes.

There are five main techniques:

(1) A Russian system developed by Kuzmin (1962, 1963) and used in research by a number of Russian investigators (e.g. Kozhevnikov and Shupliakov, 1962; Chistovich, Klaas and Kuzmin, 1962; Kozhevnikov and Chistovich, 1965; Kozhevnikov et. al., 1968).

(2) A Japanese system described by Shibata (1968).

(3) A system developed at the Massachusetts Institute of Technology by Rome (1964).

(4) A system described by Kydd and Belt (1964) of the School of Dentistry, Seattle.

(5) The Edinburgh system (Hardcastle, 1968, 1969).

The first three techniques are similar in principle but they each use a slightly different display system. A brief outline of each technique is useful for illustrating some of the problems involved in developing the technique:

1.1. The Russian System

Kuzmin's technique is called "continuous" or "mobile" palatography and the principle is illustrated schematically in Fig. 16. A necessary part of the system is an artificial palate made of acrylic material similar to that used in conventional indirect palatography (see Chapter 3, section 1.1.1.). On the surface of the palate, pairs of exposed electrodes are mounted (see Fig. 16). The electrodes are arranged symmetrically and wires from them are embedded in the artificial palate during the casting process and pass out at its posterior

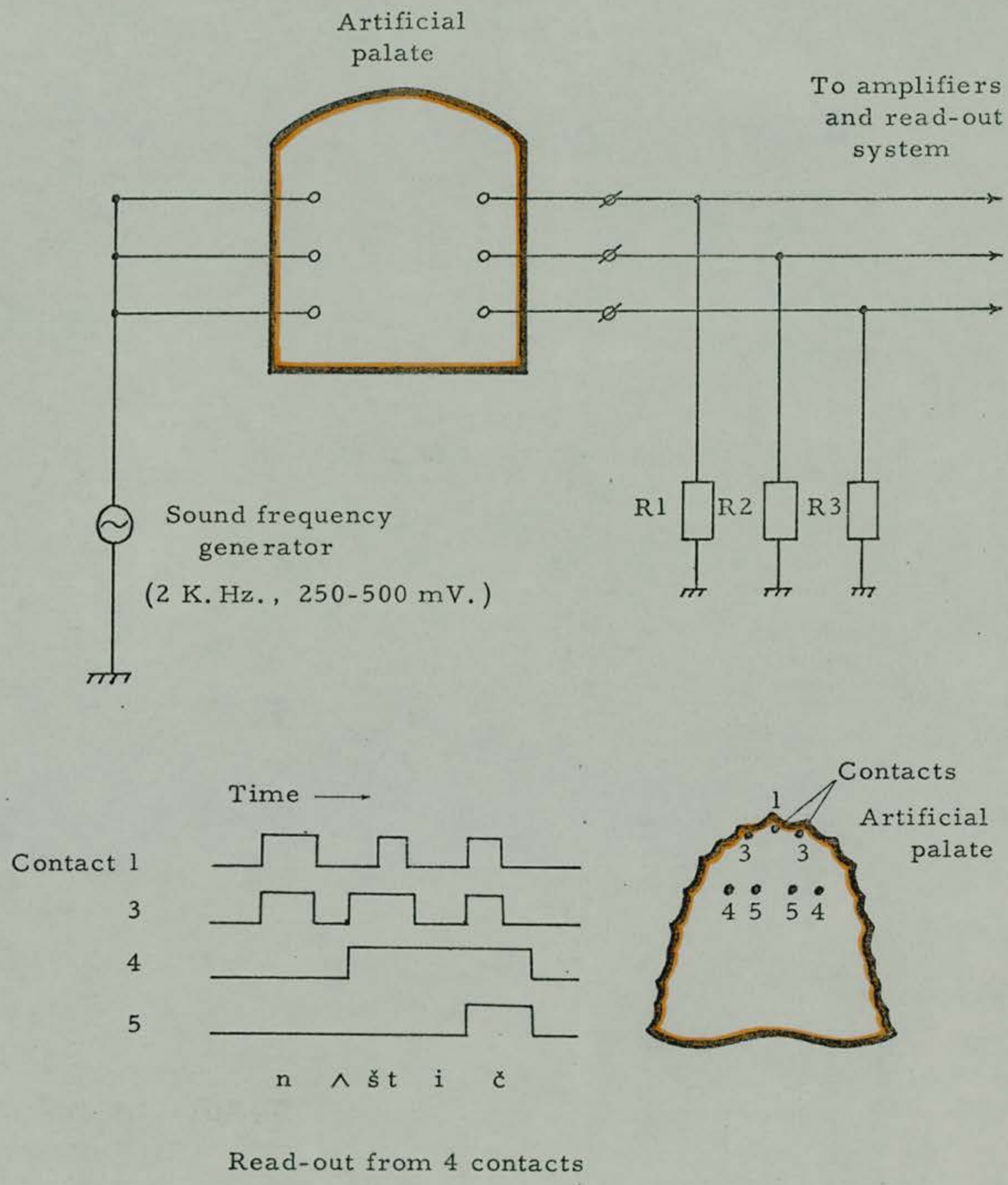


Fig. 16. Schematic diagram of the Russian system of dynamic palatography, showing the arrangement of contact electrodes and a typical read-out from four of these contacts. (from Kuzmin, 1962)

corners. Left-hand electrodes are connected to a sound frequency generator, (frequency, 2 K.Hz ; voltage, 250-500 m V).

The circuit is completed when the tongue touches both the left-hand electrodes and the corresponding right-hand ones. Signals from the palate are fed into a set of amplifiers and are registered on a multi-channel ink-recorder system.

There are a number of disadvantages of this system of electro-palatography. Firstly, the arrangement of pairs of electrodes always gives the impression of symmetrical articulation whereas in speech, the tongue often moves in a most asymmetrical fashion. X-ray laminagraphic studies (e.g. by Subtelny, 1955) illustrate this clearly. Observations of conventional direct palatography also show asymmetrical areas of tongue-palate contacts. In addition, such an arrangement of the electrodes makes the apparatus less suitable for the investigation of pathological speakers especially those with abnormal lingual articulation.

It appears that Kozhevnikov and Chistovich (1965 : 34) have realized this limitation and have suggested future modifications : for example, feeding the voltage to any mucous point in the mouth so that the entire pick-up surface can be used for mounting the "useful" electrodes. As far as this writer is aware, this has not yet been done by the Russian research workers.

Another difficulty lies in the provision of a permanent record of tongue-palate contacts. Although Kozhevnikov and his associates do not give any precise details of their methods of recording, it appears from their results as published in their most recent work (Kozhevnikov et. al., 1968), that information from only four electrode points was ever recorded at any time simultaneously. Very little detailed information concerning patterns of tongue-palate contacts is possible from such a limited sample.

1.2. The Japanese System

The paired electrode arrangement is also favoured by Shibata (1968), although in his system each member of a pair of contact points is much closer together than in the Russian system.

The technique is schematically illustrated in Fig. 17. Unlike the Russian system one of each electrode pair (64 pairs are used) is connected to a Wien-bridge oscillator for a sinusoidal source signal of an assigned frequency. The oscillators are equally spaced in frequency covering a range from 5-15 K.Hz. The palatal output signals are recorded in one track of magnetic tape, and the speech signal is recorded on the other track (see Fig. 17).

A permanent recording is provided by feeding the palatal signals into a sound spectrograph which displays the lingual contacts as a series of horizontal lines on the spectrograph paper.

The main difficulties of this system lie in relating the spectrograph to location of tongue contacts. An attempt has been made by Shibata to provide the best possible arrangement of the palatal signals on the recording paper, viz. the connection of the oscillators to the palatal electrodes, but this is rather complicated and depends on the specific points of interest of the study (Shibata, 1968 : 30).

The technique is an improvement on the Russian technique in that it utilizes more electrodes on the artificial palate so providing more detailed information on the location of tongue contacts. The disadvantage remains, however, that in any pairing system, twice as many electrodes must be used as in a system where each electrode acts as a "useful" electrode providing an independent signal. This would then be similar to the more direct modification suggested by Kozhevnikov (see section 1.1.).

1.3. The M.I.T. System

The system described by Rome (1964) is very similar in fundamental design to the Japanese. The only difference lies in the arrangement of electrodes on the artificial palate. Rome's system contains eighteen metal contacts embedded throughout one lateral half of an artificial palate. The other lateral half of the palate is effectively shortcircuited to the tongue by means of a single exposed wire that traverses back and forth across its surface. Information on precise location is only possible therefore from 18 contacts on

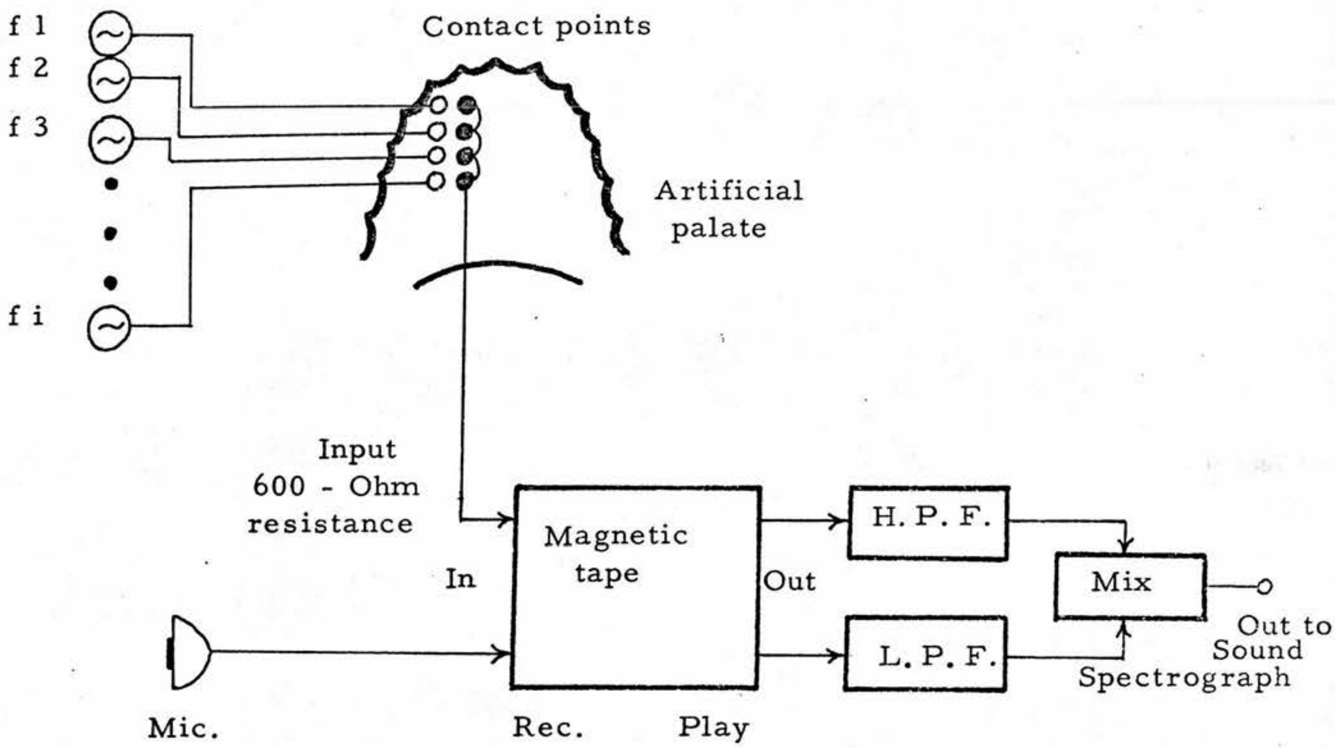


Fig. 17. Block diagram of the Japanese system of electro-palatography. (from Shibata, 1968)

one half of the palate.

A different frequency from an oscillator is associated with each contact and a permanent record is made possible by means of frequency analysis on the sound spectrograph. The technique appears to be still in the developmental stage. As it now stands it does not seem to have any advantages over the Japanese system.

1.4. Kydd and Belt's System

A more direct system using individual electrodes rather than pairs has been developed by Kydd and Belt (1964). Here exposed electrodes are also embedded in an artificial palate with the lead-out wires fed into a polyethylene plastic tube and passing out of the mouth via the buccal surface of the dentition. Each of the metal electrodes represents one pole of an electrical circuit. Unlike the other systems mentioned above, however, the opposite pole is outside the oral region, in this case a metal plate attached to the arm thus making the body (and so the tongue) a conducting medium.

Kydd's system has one set of apparatus for providing an immediate display of the contacts occurring at any one moment, and another for making a permanent record of the contacts. The display apparatus consists of a number of miniature lamps each connected through an amplifier to one of the electrodes and arranged (slightly arbitrarily) to correspond to positions in the mouth. A permanent record is provided presumably by photographing the display panel with a cinecamera, although no details as to how this is achieved are given.

Although the information from this system is rather limited as there are only twelve contact electrodes scattered more or less randomly throughout the palate, the provision of a display based on the anatomy of the palate gives a valuable conceptual simplicity which other systems lack.

1.5. The Edinburgh System

A system has been developed at Edinburgh University in the

Phonetics Laboratory which is similar in fundamental design to Kydd's system but with several important modifications that will be indicated in the next section.

In developing the Edinburgh system, care has been taken to combine a good coverage of electrodes with a better display system. With its relatively high concentration of electrodes, the Edinburgh system provides more detailed information on location of tongue contacts than any of the other systems. The crude schematic display system used by Kydd and Belt (1964) has been improved by incorporating the display lights in an actual photograph of the subject's palate. This sort of display, among other advantages, makes it much easier for the subject to relate his own tongue movements with the changing palatal contacts as he speaks. A photograph of a subject operating the instrument is enclosed in the back cover (see photograph No. 1 ,inside cover)

The difficulties in providing a suitable permanent recording remain, however. Frame-by-frame analysis of high speed cinefilm is extremely laborious. The need obviously exists for suitable processing facilities probably by computer. These difficulties will be discussed at greater length below.

2. DEVELOPMENT OF THE EDINBURGH SYSTEM OF ELECTROPALATOGRAPHY

2.1. Early Prototype

Before finally deciding on the system to be used, a number of different devices both mechanical and electrical were investigated. In the initial stages it was thought desirable to avoid, if possible, the use of any electrical current in the oral region. Thus a number of models were built and tested, based on the tongue marker principle outlined by Stetson (1951). Most of these models were simple switching mechanisms where the force of the tongue was sufficient to close the switch. Various materials including rubberized compounds were tested for this purpose.

It was soon found, however, that a mechanical system would be quite unsuitable for the purpose of recording accurately the fast lingual movements in speech. The main reason for this was the relatively slow response time of any of the mechanical systems that were built. Thus the use of electronic systems was explored.

There seemed little point in replicating the Russian "paired" electrode system as this would mean that only half the number of electrodes would be "useful". Kydd's system seemed the simplest and most efficient.

A number of test palates were built containing various numbers of electrodes spaced at intervals throughout the palate, some situated as close to each other as practicable. Initial tests were carried out to determine whether a significant signal-to-noise ratio was maintained in the presence of saliva on the contact points and whether this signal-to-noise ratio altered according to how long the palate was kept in the mouth.

On the basis of these preliminary tests, a main prototype (Prototype 1) was constructed with a palate incorporating 40 contact points, an amplification system and a display unit consisting of an enlarged photograph of the subject's palate, behind which were mounted miniature bulbs in positions exactly corresponding to the electrode positions on the artificial palate.

It became evident that to provide maximally useful information more contact points would be necessary. Thus, since the first prototype was built a number of improvements have been made to the basic design. These modifications will be discussed at length in the detailed description of the system in the next section.

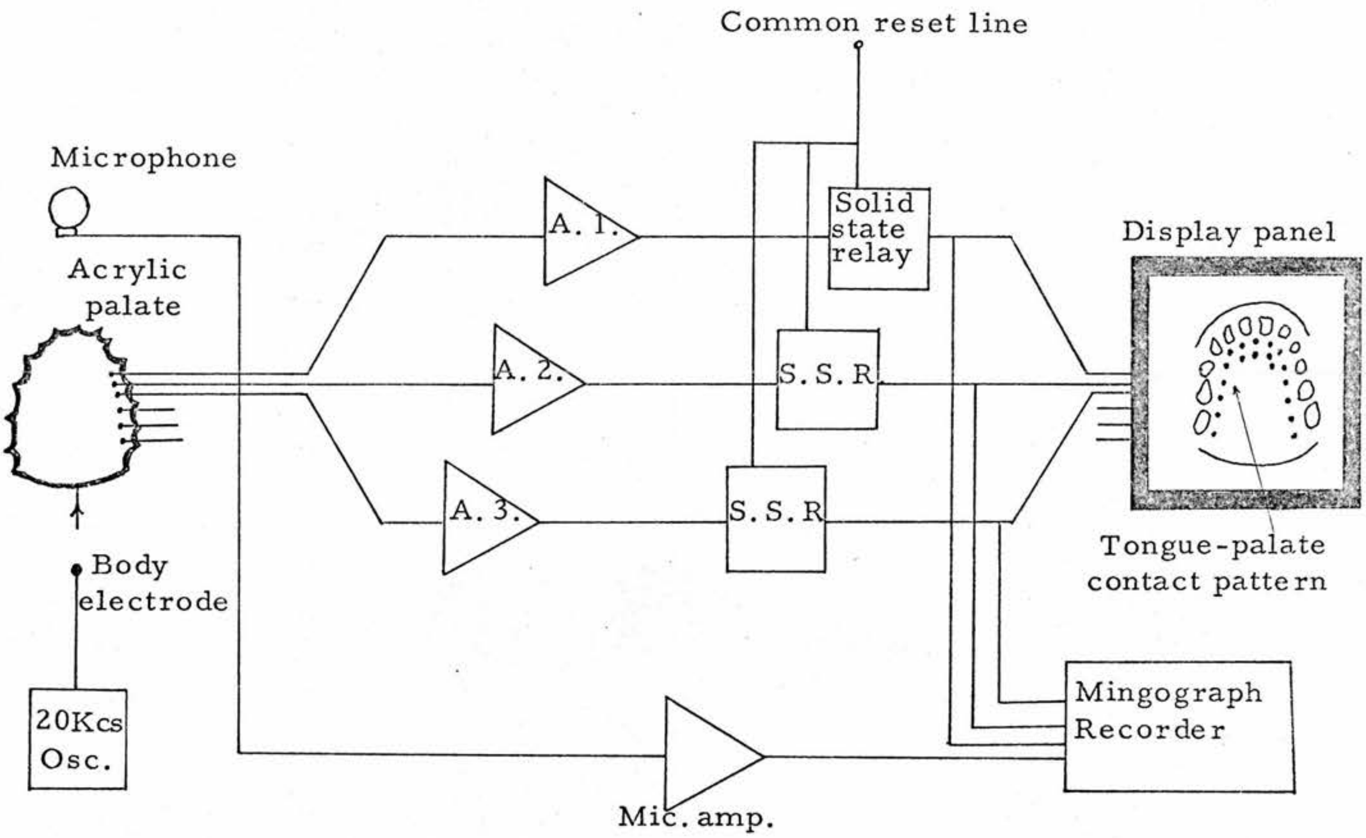
2.2. Detailed Description of the System

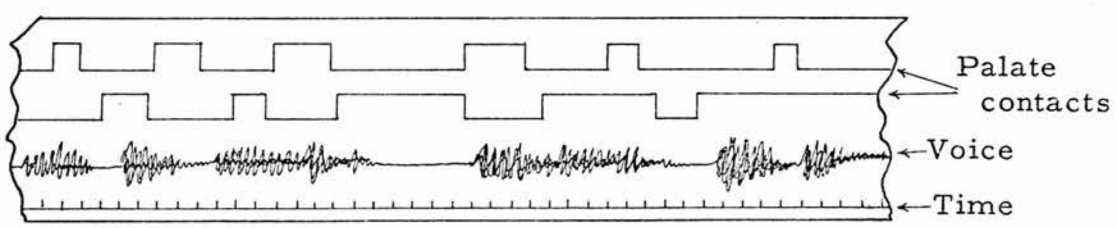
Fig. 18 shows a block diagram of the experimental lay-out. There are four major parts in the system :

(1) An artificial palate incorporating the electrodes.

(2) An electronic amplification and switching mechanism.

(3) A display unit.





Typical mingograph record

Fig. 18.Schematic diagram of the Edinburgh system of electro-palatography, showing the experimental lay-out and typical records of palate contacts from a mingograph and from the visual display panel.

(4) Apparatus to provide a permanent recording.

The development of each part of the system will be discussed in detail.

2.2.1. The Artificial Palate

2.2.1.1. Manufacture of the Palate

The material to be used in the manufacture of an artificial palate for use in electropalatography must have the following qualities:

(i) It should be strong without being too brittle.

(ii) It should not shrink or change its shape in any way.

(iii) It should be of non-conducting material

(iv) It should not break when small holes are drilled in it.

A number of different materials including dental base plates (both "Kem-Dent" and "Alston" brands), various vulcanite materials and acrylic were tested. Although dental base plate material was thin and strong enough it was far too brittle and difficult to drill. Acrylic was found to be the most suitable material for the purpose.

Two different methods of making acrylic palates are at present used by dental technicians. One involves conventional flasking techniques, the other is simpler and more efficient using a material called "Orthocryl."

The conventional technique involves first of all taking a plaster impression of the subject's mouth. This involves obtaining an impression with alginate material (e.g. "Identica") and filling the impression with plaster. An accurate plaster impression is necessary so considerable care must be taken to avoid air bubbles between the teeth, etc. By a procedure known as "waxing", a sheet of thin wax is pressed onto the plaster impression in the same shape as the required artificial palate.

The plaster cast is then placed in the lower half of a flask and plaster poured in up to the half way mark. When set, more plaster is poured into the top half of the flask forming a complete mould. The two halves are separated, the wax scraped away and enough acrylic-forming polymer and monomer mixture to make an artificial palate placed into the space left by the wax.

The two halves of the flask are clamped together with the acrylic mixture between and allowed to stand in boiling water for at least one hour. When the acrylic has completely polymerized it is removed from the plaster and rough edges cut away with a special acrylic cutter.

The main advantage of the flasking technique is that it produces an acrylic plate of uniform thickness (depending of course on the thickness of the wax used during the waxing process).

The Orthocryl method is not only much simpler but also faster. Waxing and flasking are unnecessary. The polymer and monomer materials are simply sprayed directly onto the surface of the plaster cast to the required thickness. The model is then placed in a hydroflask for about twenty-five minutes with 35lbs pressure of warm water, by which time the acrylic will have hardened. The whole process including making the plaster impression takes at most about an hour compared with four or five hours for the other method. The resultant acrylic material is the same in both cases.

Because of its many advantages, the Orthocryl method is usually used in making the artificial palates in this sytem of electropalatography.

2.2.1.2. Placement of the Electrodes in the Acrylic Palate

Electrodes are prepared by soldering tiny copper or silver discs ·015" thick and ·02" in diameter onto four foot lengths of number 41 s.w.g.enamelled copper wire. Silver electrodes have been found to be more suitable, as copper is more difficult to solder and tends to tarnish rather badly after being in contact with saliva in the mouth.

One of the most difficult problems was how to embed the electrodes and wires into the finished palate. When making the palate for Prototype I various methods were tested. One method involved drilling shallow depressions in the acrylic for the electrodes and narrow channels for the wires. The channels were filled up with liquid acrylic cement thus safely embedding the wires within the palate. Another method consisted of embedding the wires in the acrylic during the hardening process. This necessitated using the conventional flasking system and proved rather impractical with a large number of contacts. Of these two methods the channelling was probably the more successful, but it was a rather laborious and time-consuming process. There was also considerable difficulty in maintaining a smooth surface on the palate after the channels had been filled in.

A new "sandwiching" technique involving casting the wires between two thin layers of acrylic was tested and found to be most suitable for embedding a large number of electrodes and wires. In this new method, a very thin palate was made and holes drilled through it to allow the wires to be passed through. The wires were stuck to the outer side of the artificial palate (i.e. the side facing the hard palate) with acrylic cement and channelled out at the most posterior corners through polyethylene tubes (see photograph No. 2 inside back cover). Each electrode was then tested in turn with an avometer. Using Othocryl material another thin palate was made and fused onto the outer side of the first one, so sandwiching the wires between the two layers. With a little practice it was possible to construct the whole palate to be less than 1mm. thick. The main advantage of this method is the possibility of embedding a very large number of electrodes into the palate with a minimum of difficulty. The extra acrylic coating on the outer surface also protects the wires adequately and allows a convenient lead-out region at the posterior corners. By using this technique also, the danger of shorting between wires very close together, is minimized.

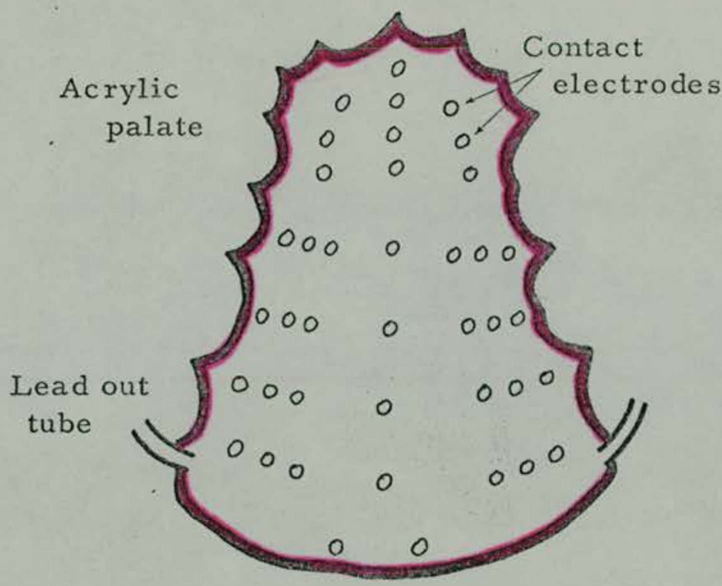
The posterior corners of the palate were found to be most suitable regions for the lead-out wires after various other sites were tested. One possibility was to lead the tubes out through gaps between the front teeth. It was thought, however, that extra thickness of acrylic for reinforcing the lead-out sites in the anterior region may interfere with articulation because of the high density of tactile sensory receptors in that area (see Chapter 2, section 1.2.2.1.). Also, if the tubes were wedged between the teeth this would severely affect the normal activity of the periodontal receptors of the teeth (see Chapter 2, section 1.2.2.), and so introduce a further experimental variable.

The most suitable place seemed to be the posterior corners, from which the tubes could travel via the buccal surface of the dentition and out through the corners of the mouth. Very little interference with lip activity was experienced from the tubes.

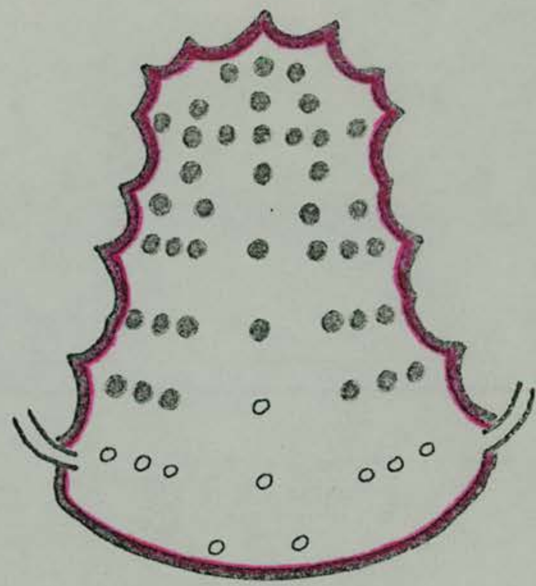
2.2.1.3. Number and Distribution of Electrodes

As mentioned earlier, the first main prototype contained 40 electrodes. These were distributed rather randomly although in general most were concentrated along the sides and in the anterior region (see Fig. 19). After experimentation with this instrument and observation of conventional palatograms, it was decided that this distribution and number was not the most satisfactory arrangement for examining English articulations. For example, some of the central electrodes appeared unnecessary as they were never touched during speech. A large number of articulations in English appeared to involve tongue articulation against the anterior part of the palate so it would be useful to have the largest concentration of electrode points in that region. It was decided, therefore, to add another ten electrodes into the alveolar region, with the facility for selecting for recording any 40 of 50 contacts, (see Palate No. 2 in Fig. 19). Another reason for concentrating the electrodes into the alveolar region was that most "complex" articulations seem to occur in this region in English (see later Chapter 5 for a discussion of "complex" articulations). These so-called complex articulations such as [s], [tʃ], [ʃ], are the subject of the research outlined in Chapter 6.

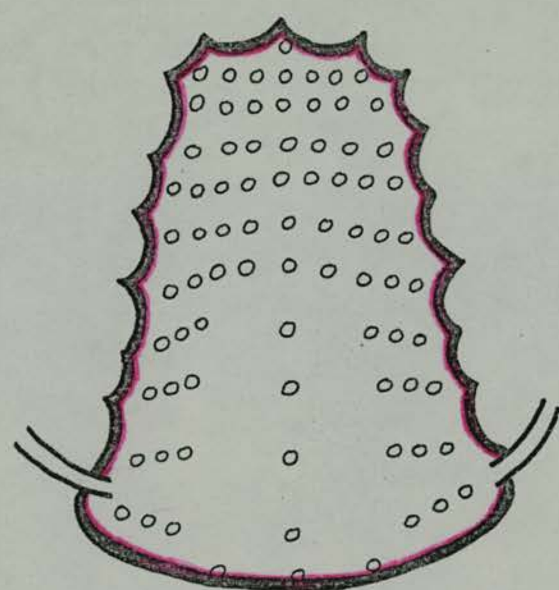
It would, of course, be desirable to have as dense a concentration of electrodes as practicable for the purpose of experimentation. A new palate has recently been built, not only including twice the number of electrodes, but also providing a different distribution, (See Fig. 19, palate No. 3.); most of the electrodes are concentrated extremely



Palate no. 1. with 40 contacts



Palate no. 2. with 50 contacts. The 40 marked contacts are those used in the experiment described in Chapter 6.



Palate no. 3. with 80 contacts

1cm.

Fig. 19. Diagrams showing the number and distribution of the contacts in the three palates described in Chapter 4.

close together in the alveolar region.

One of the main advantages of a relatively dense coverage of electrodes is that it is possible to make very detailed studies of the sequence of tongue contacts during articulation. For instance, it is possible to study in detail the sequence of contacts during the closure and release phases of affricates such as [tʃ] and from this information make hypotheses concerning the role of lingual muscles in achieving these movements (see later Chapter 5). This sort of information cannot be obtained with other techniques such as the Russians' where a relatively small number of electrodes is used.

The number and distribution of the electrodes may also be limited according to the type of experiment being conducted. For some purposes, for instance, where it is necessary only to identify broad consonant classes such as velar and alveolar stops, a smaller number of electrodes may be sufficient. For certain special purposes such as in teaching the deaf to speak or rehabilitating pathological speakers, the electrodes may be concentrated in specific areas of difficulty.

For the purpose of the present research, before the electrodes were mounted in the palate, a number of direct palatograms were made of articulations such as [s], which are of special interest in this investigation. A number of repetitions of the sounds in different vowel environments was obtained and zones of contact were drawn round those regions where wipe-off always occurred (see Fig. 20 for diagrams of these contact zones). When making artificial palates for Nos. 2 and 3 (see Fig. 19) care was taken to concentrate the electrodes mainly within those contact zones.

Although, as mentioned above, a palate incorporating 80 electrodes has in fact been built, the amplification and switching system for it is still in the developmental stage. A number of difficulties arising from the dense concentration of electrodes in the 80 contact palate have occurred (see below, section 2. 2. 2.) so it was decided to use the 50 contact palate for the purposes of the experiment described in Chapter 6.

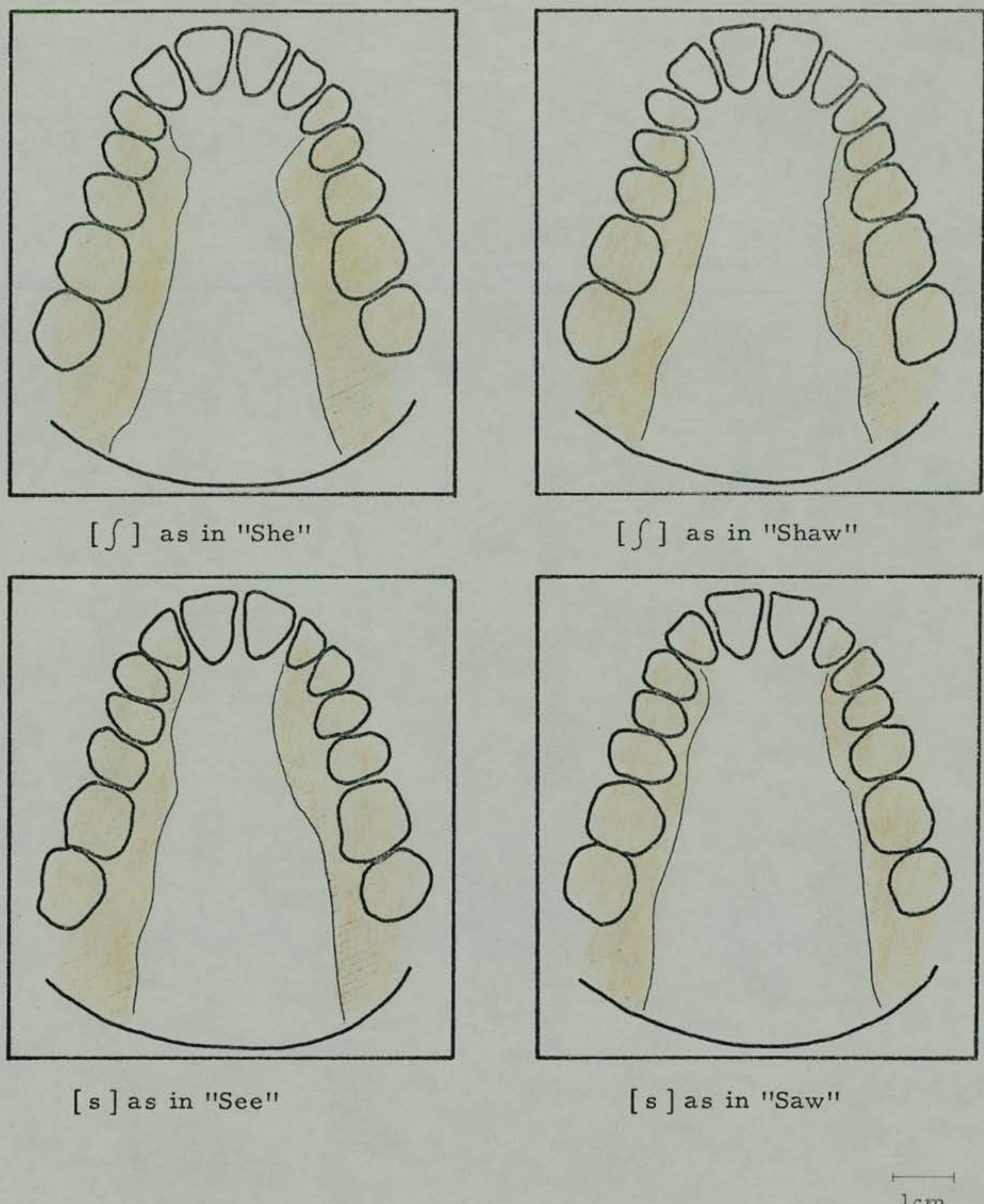


Fig. 20. Tracings made from direct palatograms of the fricatives [ʃ] and [s] in different environments. The shaded portions in the sketches represent the average areas of contact of the tongue against the palate and teeth for six repetitions of each fricative when spoken by the same subject.

2.2.1.4. Future Design of the Artificial Palate

A present a separate artificial palate must be made for each subject. Although the technique of making palates has now been refined considerably in the Phonetics Laboratory, the manufacture of individual palates is a laborious and time-consuming process. Thus the possibility of making a "universal" palate or a small number of standard palates, which would fit most subjects, is at present being investigated. The standard palates would preferably be of some malleable material which could be stuck onto the subjects' palate with dental adhesive. The electrodes could be mounted on the palate in a dense matrix arrangement such that only those necessary for a particular experiment would be selected for display.

The main difficulty with such a system is the wide difference in the sizes and shapes of palates. This is illustrated convincingly by mouth casting technique (see Chapter 2, section 1.1.1(b)). Any standard or universal palates would not give an exact fit for every subject. There are problems also in obtaining a suitable flexible material that would not lose its shape, and at the same time be strong enough to protect the wires and outlet tubes. As far as this writer is aware, no suitable material is at present available, although I.C.I. are at present experimenting with a special rubberized polymer material, which sounds rather promising.

2.2.2. Description of the Amplification and Switching Unit.

2.2.2.1. General Principle of System.

As mentioned above, the amplification and switching system used in the Edinburgh instrument is similar in general principle to that described by Kydd and Belt (1964). A current is applied to the body via a suitable body electrode and a circuit is completed when the tongue touches an electrode on the surface of the artificial palate. The signal for each electrode is amplified by separate amplifiers that drive the miniature lamps of the display unit (see below, section 2.2.3.).

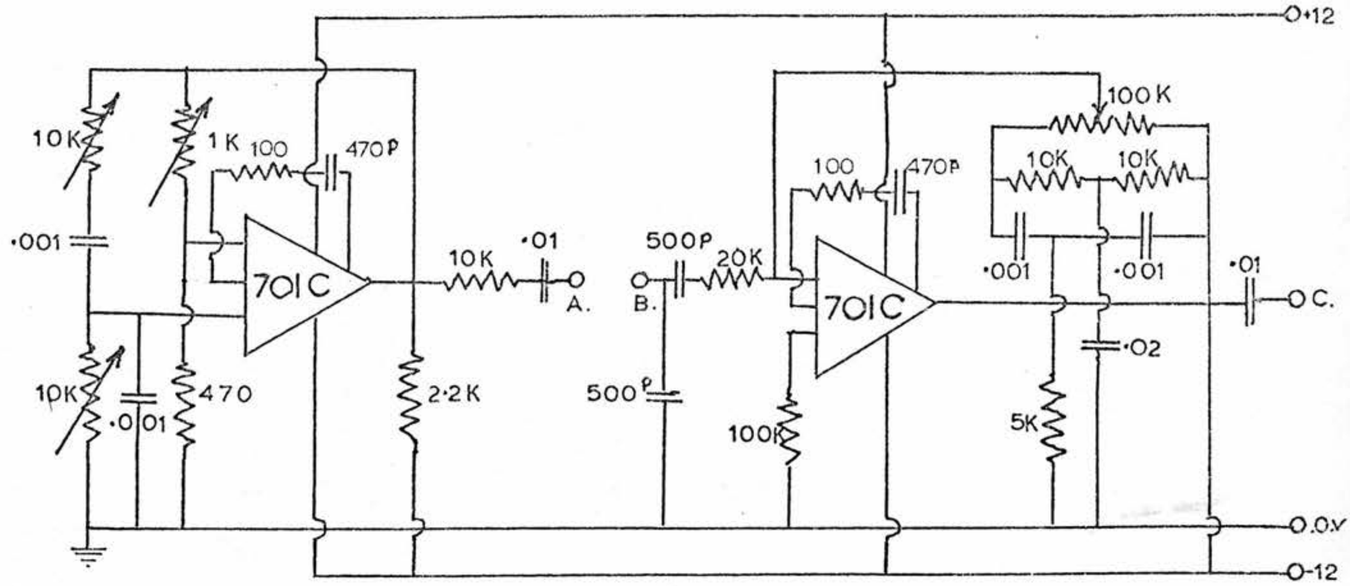
2.2.2.2. Electronic Circuitry

Fig. 21 shows the electronic circuit for the amplification and switching system used in the first prototype. An A.C. signal of 20 K.c/s. from the oscillator is applied to the body via a body electrode consisting of a grab bar made of brass held comfortably in one hand. It was decided to use a high frequency signal (20 K.c/s.) after consultation with experts in the Medical Physics Department at Edinburgh University, who recommended a high frequency A.C. signal as being most appropriate for passing current through the body (Williamson, 1969).

When the tongue touches an electrode on the acrylic palate, the signal is conducted from the body via the lead-out wires to a high impedance integrated amplifier (type SL. 701C). It is important that a high imput impedance amplifier be used at the initial stage to prevent triggering of the circuits by saliva conduction between adjacent electrodes.

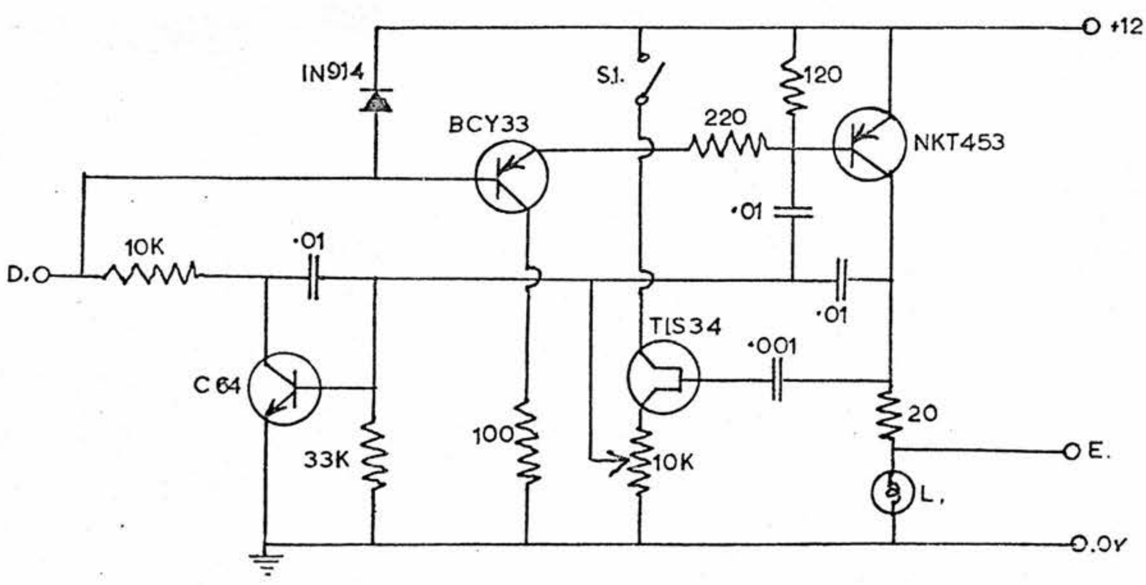
The signal is then passed through a 20 K. c/s. Band Pass filter to exclude any extraneous noises and is then used to operate a simple electronic lamp switch (see Fig. 21).

As this A.C. amplification system was rather expensive it was decided to test a simple switching D.C. system with the experimental 80 contact palate. The D.C. switch used one high impedance FET transistor and two switching transistors; the switch working with negative potential. The levels were set to 5v. It was found that with 20 to 30 electrodes on simultaneously, the machine worked satisfactorily, but when 80 were touched, the voltage had to be raised to 9v; the high voltage then caused tracking, and other unwanted



20 k/c Oscillator

Selective Amplifier



Lamp Switch

A - Oscillator Output To Hand Grip

B - Palate Electrode

C - Amplifier Output

D - Switch Output

E - Connection for Mingograph Recorder

S. 1. - Sustain Switch

L - Indicator Lamp 6 V. ·1 A.

Fig. 21. Electronic circuit diagram for the amplification and switching system used in the first prototype of the Edinburgh electropalatograph.

electrodes were inclined to come on. The D. C. system thus seemed unsuitable for a large number of electrodes.

There are a number of advantages in using some sort of D. C. system, however. The current necessary to drive the system is extremely low (about 10 micro-amps compared with 5 milli-amps for the A. C. system) and it is far cheaper. A new system using pulsed D. C. supplying 40 contacts with negative voltage and the other 40 with positive voltage is at present being explored. This would possibly prevent tracking effects where wires and contacts were close together.

For the purposes of the experiment to be described in Chapter 6, the 40 channel A. C. system will be used, the 40 channels being selected from the 50 contact artificial palate. The different electronic systems suitable for the 80 contact palate had not been sufficiently tested before this work was commenced.

2.2.2.3. Latching Mechanism

In the normal, dynamic display, the lamps go out immediately contact is broken, i. e. immediately the tongue leaves the palate. An optional facility that has been incorporated into the system is a latching arrangement, such that the lamps, once switched on, remain on. The system can thus operate either as a dynamic palatograph, with the varying light patterns reflecting the continually changing tongue contacts, or as a conventional palatograph, with the light patterns remaining static after tongue contact is made.

This sort of facility is useful for demonstration purposes and in investigating the areas of contact between the tongue and palate in those cases where timing information is not relevant.

2.2.3. Display Unit.

The display unit is a metal console housing all the electronic circuitry as well as a read-out panel. Various different designs of read-out panel were investigated. It was thought that Kydd's basic schematic display (Kydd and Belt, 1964) could be improved by substituting a photograph of the palate behind which the lamps could be mounted in positions exactly corresponding to the positions of the electrodes on the artificial palate. To achieve this, two enlarged photographs were taken of the subject's palate; the photographs were identical except that in one the subject was wearing the artificial palate. The photograph of the artificial palate showed clearly the electrode positions, and the lamps could be mounted in position on a display board using this photograph as a guide. The final display consisted of the other photograph superimposed on the lamp board. (see Photograph 3 inside back cover). One could thus be certain that the lamp positions exactly corresponded to the electrode positions on the artificial palate.

As the tongue touches the electrodes, the electronic switch activates the lamps on the read-out panel and patterns of tongue-palate contacts are seen as a number of circular spots of light. Care was taken in the manufacture of the display panel to focus the lamps in such a way that the spot of light is directly proportional in size to the circular electrodes on the artificial palate.

None of the other techniques of electropalatography described above used a visual display system such as this. It certainly seems a considerable improvement on the crude analogue diagram of the palate with 12 equally spaced contact points used by Kydd and Belt (1964). Furthermore, the provision of a display based on the anatomy of the palate, such as that used in the present unit gives a conceptual simplicity, to phoneticians at least, that other systems lack.

Future improvements could include a three dimensional display of the palate. There are two ways of doing this. One way would include two separate photographs, one of the surface of the palate photographed from directly in front, as in normal direct palatography, the other a cross-sectional view taken from half a plaster cast of the palate. This latter photograph would thus provide information on the depth of the palate as well and give a better impression of overall tongue movement.

Another type of display would consist of an enlarged model of the subject's palate based on a plaster cast impression of his mouth. The model could be made of some clear plastic material and the lamps fitted inside. This would probably be the most conceptually simple display.

2.2.4. Apparatus to Provide a Permanent Recording

To obtain quantitative information about tongue-palate contacts, a permanent record of these contacts needs to be made. Such a record can be obtained in three ways:

(1) By connecting the output from the electrodes to a multi-channel ink recording system such as a Mingograph.

(2) By photographing the display panel with a high-speed cinecamera.

(3) By feeding the outputs in digital form into a computer storage system.

2.2.4.1. Mingograph Read-out System

A Mingograph recording system is used to provide a permanent record of specific points of contact in the Russian technique (Kuzmin, 1962). Fig. 16 shows a typical read-out from four contact points.

This type of read-out system is very useful if one wishes to record the output from a limited number of electrodes only. In the Edinburgh Phonetics Laboratory, it is possible to record the read-out from any sixteen electrodes by using the 16 channel Mingograph. It may be possible to devise a system whereby more than one electrode is fed into one channel. Such a system would be rather limited, however, because of the problem of differentiation.

Because of the relatively small number of contact points involved, the problem of processing the data is not great using this system. It is convenient, for example, in obtaining quantitative data on the frequency of tongue contacts at a particular point or small number of points on the palate during speech.

2.2.4.2. Cinephotography

A permanent record of all the contact points is available by photographing the display panel with a cinecamera. There are a number of problems associated with this system however. Firstly, a suitable camera speed must be used to give maximally useful information without making the problem of data-handling too difficult. In a preliminary experiment,a camera speed of 60 frames per second was used on a mechanically driven camera. This speed was found to be too slow however to record maximally useful information on details of rapid lingual movements, for example, the lateral contacts in approach and release phases of taps. On the basis of this, the speed was increased to 100 frames a second, which was found to be sufficient for most purposes. The mechanically driven camera was discarded in favour of an electrically controlled model after it was found the camera speed in the former tended to fluctuate from 40 to 65 frames a second. This would make it quite unsuitable for obtaining accurate timing measurements.

Another problem lies in synchronizing the cine-film with the audio signal, so that correlations can be made between the lingual contacts and acoustic spectra measured on the spectrograph. After a number of tests a synchronization system was designed for use in cine-photography. It consists of the following units:

(1) An electronic counter, with a visible display giving real-time in .25 sec. steps. This is situated in the upper left-hand corner of the display panel and is thus photographed with the main display unit.

(2) A click generator producing a narrow band 4 K. c/s signal at .25 sec. intervals.

(3) A double track tape recorder.

The electronic counter and click generator are connected via a switch to the cinecamera. When the switch is operated, the electronic counter and click generator begin simultaneously with the camera. The click signal is fed onto one track of a two-track tape recorder. The other track has the audio signal from the microphone. The two tracks are eventually mixed and spectrograms made of the audio signal. The high frequency click is seen as a narrow spike in the upper quarter of the spectrogram.

Because the timing clicks are synchronized with the counter on the display panel, it is possible to select any point on the spectrogram and obtain a detailed record of the location of tongue contacts at that precise time from the particular frame. The main problem with the cinephotography system, however, lies in the processing and presentation of the data. It is possible, of course, to present the data as a series of film frames (see Fig. 22 for sequence of tongue contacts for [tʃ],), but difficulties are involved when attempts are made to quantify the data. It would be a relatively simple matter to obtain graphs of the total number of contact points as a function of time, but this would give no useful information on the precise location of the contacts. Graphs can be drawn, however, illustrating certain aspects of specific movements. Thus Fig. 23 shows a graph of tongue movement from the back of the palate to the front for the articulation [ʃ]. A graph such as this would show, for example, the rate of lingual movement and the effect of different environments. The tongue may not move so far forward, for example, when [ʃ] was followed by [a] as when followed by [i]. By using a vertical zoning scheme on the palate (see, for example, Fig. 23) it may be possible also to give an indication of the narrowness of the central groove in fricative articulations such as [s] at any particular horizontal section of the palate. Such a display is useful for providing quantitative data for the experiment described in Chapter 6.

2.2.4.3. Computer Storage

Analysis of data obtained from the Mingograph system or cinephotography tends to be a rather laborious process. A convenient means of processing the data may be by computer.

The advantage of such a system seems obvious and experimentation is at present being carried out to explore this possibility. The most promising scheme seems to be to use a ring counter system which scans all the outputs from the electrodes at a very high frequency and provides a digital input for a computer. Data can then be extracted by line printer, etc. Using such a system it should be possible to analyse

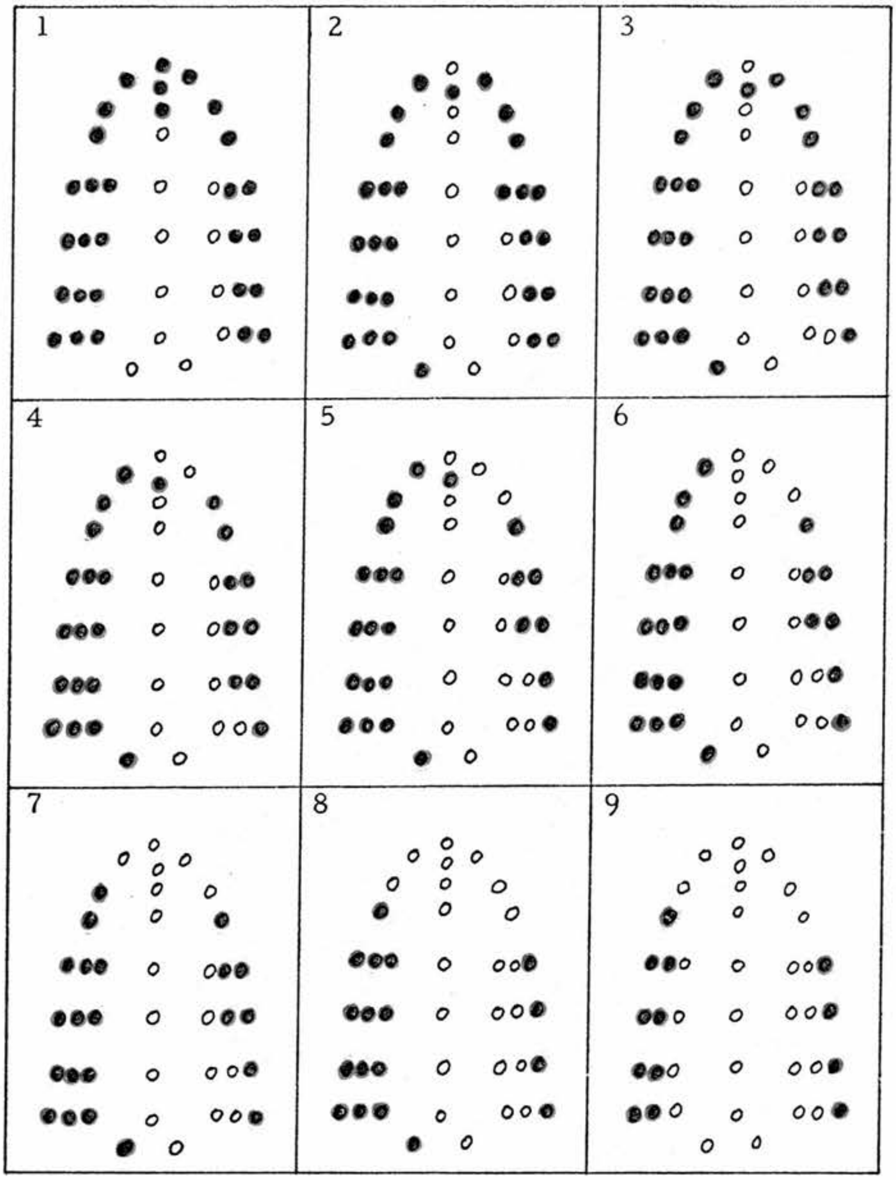


Fig. 22. Tracings from a cine-film of the electropalatography display screen taken during the release of the affricate [tʃ]. The nine tracings represent consecutive film frames with the pattern of contacts corresponding to those on palate no. 1 in Fig. 19. The camera speed was 50 frames per second.

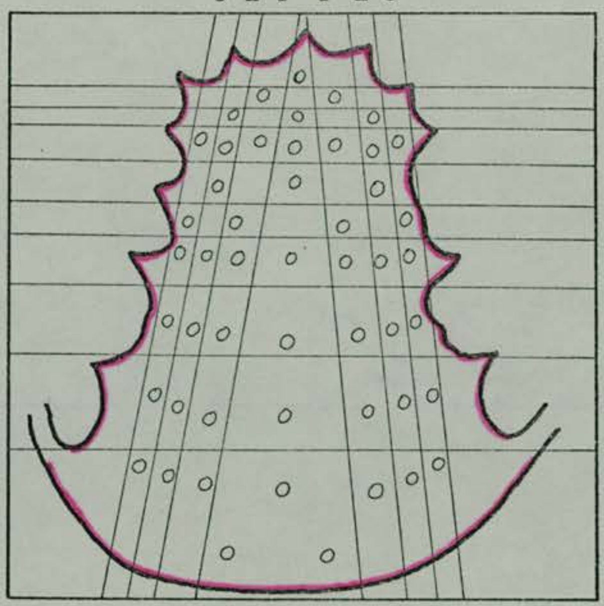
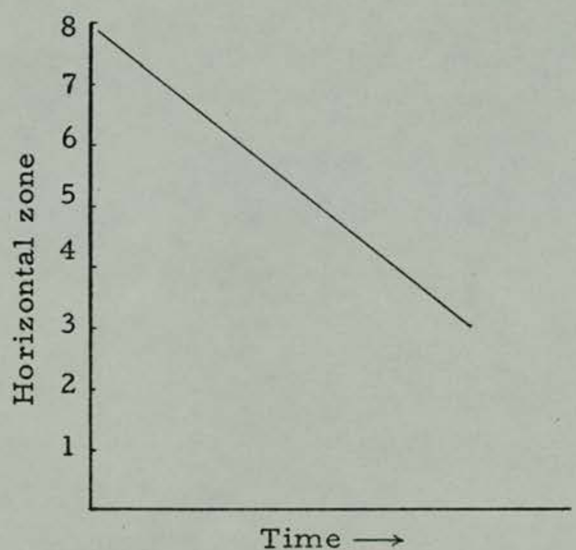
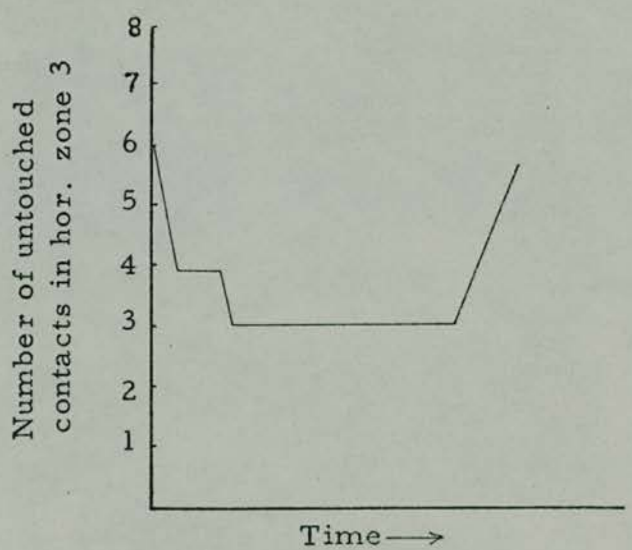


Diagram of horizontal and vertical reference zones for contacts in Palate no. 2 (Fig. 19)



Graph of tongue-palate contacts in the approach to [ʃ] in [aʃ].



Graph of narrowness of central groove for [ʃ] in [ɛʃɔ].

Fig. 23. Diagram of the reference zoning scheme for the palate contacts, and two graphs illustrating certain aspects of tongue movements. For a more detailed discussion of this sort of graphical representation of lingual articulation, see later Chapter 6, section 3.

a large quantity of material rapidly and efficiently.

2.3. Future Electropalatographic Design

At present the electropalatograph registers tongue contacts only; it gives no indication of pressure of contact. The possibility of using pressure sensing systems such as piezo-electric crystals, miniature strain gauges and pressure sensitive paint is at present being explored.

Miniature strain gauges seem to offer the most promising avenues of research as they have already been used extensively by dental research workers to register lingual and other soft tissue pressures at specific points in the oral region (see Chapter 3, section 1.1.3.2.). The main difficulties of these systems would be in mounting a sufficient number of strain gauges on the artificial palate such that they could register differential pressures at different points. The mechanical difficulties of mounting a fairly large number (e.g. 20) would be considerable. However, engineers at a recent Semi-Conductor Exhibition in London believed that the use of strain gauging for this purpose was feasible.

It is interesting to note that just as dental research contributed to the development of direct and indirect palatography (Abercrombie, 1957), it seems that it has much to offer in this new field of phonetic research also.

Another future possibility is adapting Hillix, Fry and Hershman's capacitance technique (1965) to register not only contact but proximity of tongue to the palate. To obtain any detailed information on the position of the tongue a number of capacitors suitably shielded from each other would be necessary. Ultrasonic techniques (see Chapter 3, section 1.1.2.) could perhaps also be utilized to obtain proximity data. More research is needed to explore the feasibility of this. One modification that must be made in the future is the provision of an adaptable palate. This has already been briefly discussed above (section 2.2.1.4.). More research is needed to develop a suitable material for such a palate. It is certainly necessary if any large scale projects involving many subjects are to be undertaken.

An ideal electropalatographic system would thus register not only timing and location of tongue contacts with the palate but the pressure of contact and proximity of tongue to the palate as well.

3. PRACTICAL APPLICATIONS OF ELECTROPALATOGRAPHY

As mentioned earlier, there are a number of practical applications of electropalatography apart from its use in experimental phonetic research. These are :

(1) Education of the deaf.

(2) Diagnosis and rehabilitation of pathological speakers

(3) Teaching foreign languages.

(4) Providing information for writing control-programmes for physiological synthesizers.

(5) Applications for the study of oral physiology.

3.1. Education of the Deaf

Profoundly deaf children experience difficulty in acquiring speech mainly because they have no possibility of auditory feedback and must rely almost entirely on their own proprioceptive and tactile feedback to monitor their production of sounds (see Chapter 2). By imitating prescribed patterns of tongue-palate contact on the electropalatograph, the deaf child may be encouraged to develop his tactile and proprioceptive sensory feedback information as associative learning stimuli substituting for the basically auditory speech-stimuli in the normal hearing child.

In the classroom situation, it would be possible for the teacher to monitor each child's articulations at a central display unit similar to the situation in a typical language laboratory. As the technique now stands, however, it would be necessary to manufacture a separate palate for each child. A standard palate system would be extremely useful in this respect.

A number of speech therapists and teachers of the deaf have recently expressed interest in the use of electropalatography for this purpose after a demonstration on BBC's "Horizon" programme and at a meeting of the

Scottish Area of the School of Speech Therapists (Royal Infirmary, Edinburgh, 1970). The technique may prove to be particularly useful in refining certain articulations of deaf children after they have learnt to vocalize using various electronic aids (Montgomery, 1970). As a supplementary aid to electronic systems such as fricative and nasal indicators (Risberg, 1970), the technique of electropalatography may also prove useful.

3.2. Diagnosis and Rehabilitation of Certain Pathological Speakers

The use of electropalatography as a diagnostic and rehabilitatory aid in speech therapy is at present being explored. At the recent demonstration of the electropalatograph at the Area Meeting of the College of Speech Therapists mentioned above, a number of members expressed opinions that electropalatography would be an extremely valuable diagnostic aid for certain disorders of articulation, particularly some types of dysarthrias and dyspraxias. The dynamic nature of the display also may make the technique particularly useful in treating difficulties in timing articulations correctly. It may be possible to devise a scheme whereby different time intervals associated with articulations can be readily discernible on the display screen. This idea was suggested by Fant (1970).

3.3. Foreign Language Teaching

Another such application may be in teaching foreign languages. Here electropalatography could be used by the student as a supplementary aid to machines such as the tape recorder providing auditory feedback. As Abercrombie (1957) mentions when writing about the use of direct palatography for teaching purposes, "Articulatory movements which are not visible are not easy to grasp for beginners in phonetics, whose kinesthetic sense is usually still undeveloped for the tongue. Descriptions of these movements can be made more real and less purely theoretical by means of palatography" (p. 25). The same would apply even more so to electropalatography.

Electropalatography may be useful also as a demonstration aid for the teacher of general phonetics illustrating for instance closure positions for more exotic articulations such as velaric clicks.

3.4. Physiological Synthesizers

An important application of electropalatography, and one which is linked closely with the main motivation for developing the technique is its use in providing information for writing control programmes for physiological synthesizers, in order to test articulatory assumptions in theoretical phonetics.

3.5. Oral Physiology

Lastly, a general application for the technique is in providing information for use in oral physiological research. Details of lingual contact with the palate during chewing and swallowing will be particularly useful for dental research workers especially when the extra facility of pressure registration is added.

Information on the frequency of lingual contacts at particular points on the palate will also be useful in designing dental appliances (Watt, 1969).

4. LIMITATIONS OF ELECTROPALATOGRAPHY

Although most of the limitations of the technique have already been suggested, it may be useful to summarize them here. It must be emphasized that the technique is still in the experimental stage and various modifications are still necessary to make it a maximally useful research tool in experimental phonetics. The main limitations will be discussed briefly.

4.1. Interference with Articulation

The possibility of foreign bodies in the mouth interfering with articulation has already been mentioned in Chapter 3, section 1.1.1. To assess the degree of interference using the artificial palate, various features of articulation such as duration, intensity and acoustic frequency associated with fricative articulation were investigated experimentally with the use of sound spectrography,in the normal condition and with the palate in the mouth. No significant differences were noted. This finding agrees with Kozhevnikov and Chistovich's results (1965 : 27) where they found "a monitored determination of the intelligibility of speech conducted on one of the subjects showed that wearing the pick-up hardly affects the pronunciation. The syllabic intelligibility of the pick-up, taking standard syllable tables into account, comprised 87.5% while under the same conditions but without the pick-up, this intelligibility was 89%."

Any possible interference from the palate is minimized if it is made thin enough. Using the "Orthocryl" technique described earlier in this Chapter, it is possible to make an artificial palate as thin as one mm. including contacts.

A recent experiment described by McDonald and Aungst (1967), where the subject's palate was covered with wax and the effect noted on oral stereognosis ability in the mouth, suggests that the sensory resources in the palate do not play a large part in sensory discriminations in the mouth. It may be, of course, that the interference is compensated for in other ways by the oral structures, but this is difficult to assess experimentally.

4.2. Placement of Electrodes

Because of the discrete placement of electrodes, it is not possible to obtain a complete coverage of the palate so a sampling problem arises. The electrodes, however, can be very closely concentrated in particular areas of interest on the palate, for example, the alveolar region. There are added difficulties in placing the electrodes too closely together; the acrylic material separating them may deteriorate so causing shorting to occur, or unwanted capacitance effects may result from wires crossing each other or approaching each other too closely.

4.3. Non-uniformity of Palates

Mouth casting technique (see Chapter 3, section 1.1.1.) have illustrated the wide differences in palate shapes and sizes. This makes it particularly difficult to design a standard, adaptable palate. Such a standard palate, as mentioned above, would probably be necessary if a large number of subjects, such as a class of deaf children make use of the technique.

As the technique now exists, however, a separate palate must be made for each subject. There is then the added difficulty of comparison between different subjects. This difficulty was discussed earlier when describing the technique of static palatography (see Chapter 3, section 1.1.1.).

4.4. Limited Information from the Technique

Because of the nature of the system, electropalatography as it now stands is only suitable for investigating articulations involving lingual contact with the palate. Detailed information is thus available on the location of tongue contacts associated with most contoid articulations and on the timing of the lingual movements involved. Thus the machine can register not only place of articulation, but also temporal aspects of manner of articulation as well.

The technique is not suitable for investigating articulations such as some open vowels where no contact is made, nor for post-velar contacts: but dental contacts can be explored, depending on palate construction. The possibility of registering proximity of the tongue to the palate has already been suggested as an important modification for the technique.

CHAPTER 5

PHYSIOLOGICAL SPECIFICATION OF SOME ARTICULATORY PARAMETERS

1. THE PLACE OF PHYSIOLOGY IN PHONETIC THEORY

As indicated earlier (Chapter 1), one of the most important aims in current phonetic research is to describe accurately the events of speech production. These may include not only the positions and movements of various muscles in the oral region, but also the co-ordination, both temporally and spatially, of these muscular activities by neurological functions. With a detailed knowledge of the anatomical and physiological structure of the oral system such as that outlined in Chapter 2, and experimental data from various instrumental techniques such as those reviewed in the last two chapters, one can proceed to synthesize this information and to begin to suggest more adequate physiological correlations of basic articulatory parameters. It should be indicated that in this context, "articulation" at the phonetic level refers to the changing surface configurations of the vocal tract, while "physiology" refers to the means by which these changes are achieved. It is not proposed here to develop a complete physiological theory of phonetics, but merely to indicate the direction that attempts to formulate such a theory should take. Most of the material discussed in this chapter is highly speculative, but if it opens up promising avenues of research it will have served its purpose.

2. CORRELATIONS BETWEEN PHYSIOLOGICAL MECHANISMS AND ARTICULATORY PARAMETERS

To a certain extent, it is already possible, in a gross way, to specify some physiological aspects of phonetic theory. Some basic articulatory categories, for example, can be correlated with specific groups of lingual muscles or specific muscular activity. Some such categories will be discussed briefly:

2.1. Vocoids and Contoids

In Chapter 2 it was seen how the muscles of the tongue can be conveniently divided into an extrinsic and an intrinsic group. The extrinsic group, consisting of the genioglossus, styloglossus, hyoglossus and palatoglossus muscles have their origins outside the tongue and are mainly responsible for altering the gross position of the body of the tongue in the mouth. The intrinsic muscles, on the other hand, comprising the superior and inferior longitudinalis, the verticalis and the transversus are located entirely within the body of the tongue and so are responsible for the most part for altering the shape of the tongue only.

The two muscle groups differ anatomically as well as functionally. In general, the extrinsic muscles are larger, slower, capable of exerting greater tension. Intrinsic muscles by contrast, are smaller, faster, lighter and usually relatively incapable of exerting great tension. The intrinsic muscles also probably have much lower innervation ratios of the motor units innervating them than the extrinsic muscles (see Chapter 2, section 1). This means the intrinsic muscles are capable of producing a wide variety of delicately controlled lingual shapes, whereas the extrinsic muscles are capable mainly of achieving gross differences in the position of the tongue.

The two muscle systems can be correlated to a certain extent with two of the most basic phonetic categories - vocoids and contoids (Pike, 1943 : 78). The articulation of vocoids primarily involves gross positioning of the tongue body irrespective of the delicate adjustments of the surface configuration: the extrinsic system probably is mainly responsible for this. Contoids, on the other hand, require not only positioning of the tongue body at certain points in the oral region, but also often extremely delicate adjustments of surface configuration. Contoid articulation thus probably utilizes both the extrinsic system for the gross movements and the intrinsic system for the delicate shape adjustments.

The possible interaction of the extrinsic and intrinsic systems in the production of vocoids and contoids generatessome interesting hypotheses regarding co-articulation phenomena. The interaction of the extrinsic and intrinsic muscle groups can help to explain, for instance, co-articulation features in a VCV-type sequence. Here the contoid articulation can be regarded as a gesture superimposed on a basically diphthongal, extrinsically-achieved V-V gesture. (Öhman, 1967; Perkell, 1969).

The intrinsic system, responsible for any delicately controlled tongue configuration required for the contoid, may be regarded as acting largely independently of the slower, continuously-varying vocoid-producing system. Thus in a syllable such as [a s i], the particular tongue configuration for the [s], involving among other things the production of a central groove by the intrinsic musculature, is probably beginning to be formed during the articulation of [a].

2.2. Physiological Correlates of Certain Contoid Manner Categories

2.2.1. Stop and Fricative

Proceeding along similar lines to those outlined in section 2.1., it is possible to describe many of the manner categories of articulation in physiological terms. In the process of occluding the tongue against the palate for an alveolar stop, a "ballistic" type movement, i.e. one involving primarily protagonist muscles acting alone, is probably employed. A fricative, on the other hand, requires a far more delicate balance of protagonist and antagonist muscles to create the specific stricture required to maintain the turbulent flow of air necessary for its production. In general terms then, fricatives can be said to require more delicate neuromuscular control than stops. The concept of delicacy or complexity will be examined more closely in section 4.

2.2.2. Stop and Tap

Another physiological correlate, rate of muscular activity, may be used to distinguish between stops and taps. As with a stop, tap articulation requires gross positioning of the tongue body by the extrinsic system and a rapid contraction of muscles such that one articulator is thrown against another. In this respect it is similar to the ballistic movement of a stop. A major difference, however, lies in the rate of movement; the tap being very much faster. There may also be aerodynamic factors involved, caused by the speed of articulation, which do not apply to a stop. It is interesting to note that most taps seem to occur in the dental and alveolar regions (Ladefoged, 1967b: 33). The muscles of the tongue tip system that are primarily responsible for tap articulation (i.e. superior longitudinalis and verticalis) are probably the only muscles in the tongue capable of such rapid contractions necessary for tap articulation. One of the reasons for this is perhaps that these intrinsic muscles are in general lighter and smaller than other tongue muscles and so in general may contract faster (see Cunningham, 1964 : 268). This is perhaps why tap articulation usually occurs in the front part of the mouth with apical articulation.

2.2.3. Flap Articulation

Flap articulation is different from a tap in that it usually involves retroflexion of the tip and a forward movement striking or "flapping" against the alveolar ridge as it passes. The movement is essentially an apical movement and in this respect it is similar to a tap. Both movements probably employ similar extrinsic and intrinsic muscles, the superior longitudinalis being the protagonist muscle. The degree of tension exerted by the superior longitudinalis in the flap, however, is probably considerably greater than in the tap. The greater degree of contraction produces an upward backward movement of the tip and blade essential for retroflexion; an upward movement only is sufficient for tap articulation.

2.2.4. Trill

In the articulation of an alveolar trill, the tongue tip is held, by balanced contraction of protagonist and antagonist muscles of the intrinsic and extrinsic group, lightly against the alveolar ridge and set in vibration by the airstream passing out through the oral cavity. The control necessary to place the tip in the correct position probably comes primarily from the superior longitudinalis muscle with anterior genioglossus and inferior longitudinalis acting as antagonists. The rate of vibration of the tip against the alveolar ridge, contingent upon such factors as tension of the muscles, velocity of air-flow, closeness of constriction, etc., can be quite high, up to at least 30 c.p.s. (Stetson, 1951).

The physiological mechanisms involved in trill articulation are thus quite different from tap or flap articulation although they can all be produced in roughly the same area of mouth using the same articulators. The _degree_ of controlled muscular contraction, i.e. the degree of interaction between protagonist and antagonist muscles necessary for trills is similar to that used by fricatives, so there is probably some justification in regarding a trill as physiologically more similar to fricative articulations than to tap or flap articulations.

2.2.5. Problems Involved in Formulating Relationships Between Particular Physiological Mechanisms and Articulatory Manner Categories

. It was seen above how it may be possible, at a simplistic level, to specify some basic articulatory manner categories in terms of physiological mechanisms underlying them. For example, one can posit a general relationship between the contributions of different muscular systems of the tongue and the basic division of sounds into vocoids and contoids; vocoids using principally the extrinsic muscle system and contoids both the extrinsic and intrinsic systems. However, between different contoid articulations, the involvement of extrinsic and intrinsic systems may vary considerably. Thus, within the manner category _stop_, articulations involving the back part of the tongue, e.g. velar stops, may adopt very different tongue postures from alveolar articulations; one can probably even go so far as to say velar stop articulations make more use of extrinsic muscles than do alveolar stop articulations, where the particular tongue configuration required relies to a larger extent on intrinsic muscles such as superior longitudinalis and verticalis to form the closure with the tip and blade.

Another difficulty arises when one attempts to posit different physiological mechanisms for different manner categories such as those mentioned above. What are often regarded as two different manner categories may rely on rather similar physiological mechanisms for their articulation. Thus as was seen above, trill articulation may be more similar physiologically to fricative articulation than to tap or flap articulation.

As our knowledge of the physiology of the oral region becomes more complete, it will become easier to posit one-to-one relationships between articulatory parameters and physiological mechanisms. If then a particular manner category has no one-to-one relationship with some physiological mechanism it would perhaps have to be revised. Various recent attempts to specify more closely the physiological mechanisms of speech (e.g. by Peterson and Shoup, 1966; Ladefoged, 1967b.), have met with limited success, but much more detailed research is necessary before we can confidently specify any one-to-one relationship between articulatory and physiological activities. (A start can be made, however, in attempting to provide more detailed physiological correlates for different lingual articulatory parameters). The next section is an attempt to specify a number of lingual articulatory parameters and what may be the physiological mechanisms underlying them.

3. PHYSIOLOGICAL CORRELATES OF LINGUAL ARTICULATORY PARAMETERS

One of the main difficulties in providing physiological correlates of phonetic categories has been the relative lack of any adequate detailed descriptive model of lingual articulation. This is seen for instance in attempts to specify vowel quality in physiological terms. For many years the traditional way of specifying vowel quality has been nominally in terms of the "highest point of the tongue" and position of the lips. However, specification in terms of the "highest point of the tongue" neglects to a large extent the overall shape of the tongue, which may have important effects on vowel quality. For this reason some phoneticians have suggested additional articulatory parameters for specifying the shape of the tongue such as "narrow and wide" (Sweet, 1906) and "tense and lax" (Jakobson and Halle, 1964). As Sweet, (1906) explains, " in forming narrow vowels there is a feeling of tenseness in that part of the tongue where the sound is formed, the surface of the tongue being made more convex than in its natural "wide" shape, in which it is relaxed and flattened" (p. 19).

The physiological explanations of different tongue motions and configurations has, to this writer's knowledge, never been adequately specified. As Ladefoged (1967b) says, "There seems to be no simple set of parameters which is equally appropriate for specifying the tongue shapes of all these vowels" (p. 43). Such a set of parameters is particularly important for contoid articulation where, as was indicated earlier, specific tongue configurations are necessary for certain manner categories of articulation .

On the basis of the comprehensive outline of the anatomy and physiology of the tongue musculature (Chapter 2) and information from experimental techniques such as palatography (both direct palatography and electropalatography) and radiography, it should be profitable to try to describe the known tongue shapes and motions used in speech production as the results of the interaction of a minimum number of articulatory parameters. It should then be possible also to specify the lingual physiological mechanisms underlying a given articulatory parameter at least on a speculative basis.

One of the difficulties in formulating such a set of parameters is the extreme versatility of the tongue. As mentioned earlier, because of the interaction of two complex muscular systems, the extrinsic and intrinsic system in the tongue, the organ is extremely mobile, capable of an almost infinite variety of different movements and configurations. Not all these movements and configurations, however, are important for speech production: those important for speech can be substantially specified in terms of the interaction of seven different parameters describing not only movements of the tongue in the vertical and horizontal sagittal plane but also different transverse shapes. As seen earlier, the tip can move independently of the rest of the tongue so a broad functional division between the body and the tip-blade system is useful. The boundary of the tip-blade system can be fixed arbitrarily as the point on the dorsum opposite the junction between the alveolar ridge and hard palate when the tongue is in a position for the articulation of [ə].

Movements of both the tip-blade and body systems can be described in relation to a fixed point within the body of the tongue. A convenient point is the point sometimes chosen as a common point of reference for x-ray measurements of lingual dimensions (see Wildman, 1961). This is the point of intersection of a line drawn from the tip of the lower incisor to the centre of the second cervical vertebra and another line drawn vertically from the junction between the hard and soft palate (see Fig. 24).

The seven parameters for specifying the different lingual motions and configurations during speech can be described briefly as follows:

(1) Tongue body system : horizontal forward-backward movement (see Fig. 24).

(2) Tongue body system : vertical upwards-downwards movement (see Fig. 24).

(3) Tip-blade system : horizontal forward-backward movement (see Fig. 24).

(4) Tip-blade system : vertical upwards-downwards movement (see Fig. 24).

(5) Transverse cross-sectional configuration of the tongue body : convex-concave, in relation to the palate (see Fig. 25).

(6) Transverse cross-sectional configuration extending throughout the whole length of the tongue, particularly the tip and blade: degree of central grooving (see Fig. 25).

(7) Surface plan of tongue : spread or tapered (see Fig. 26).

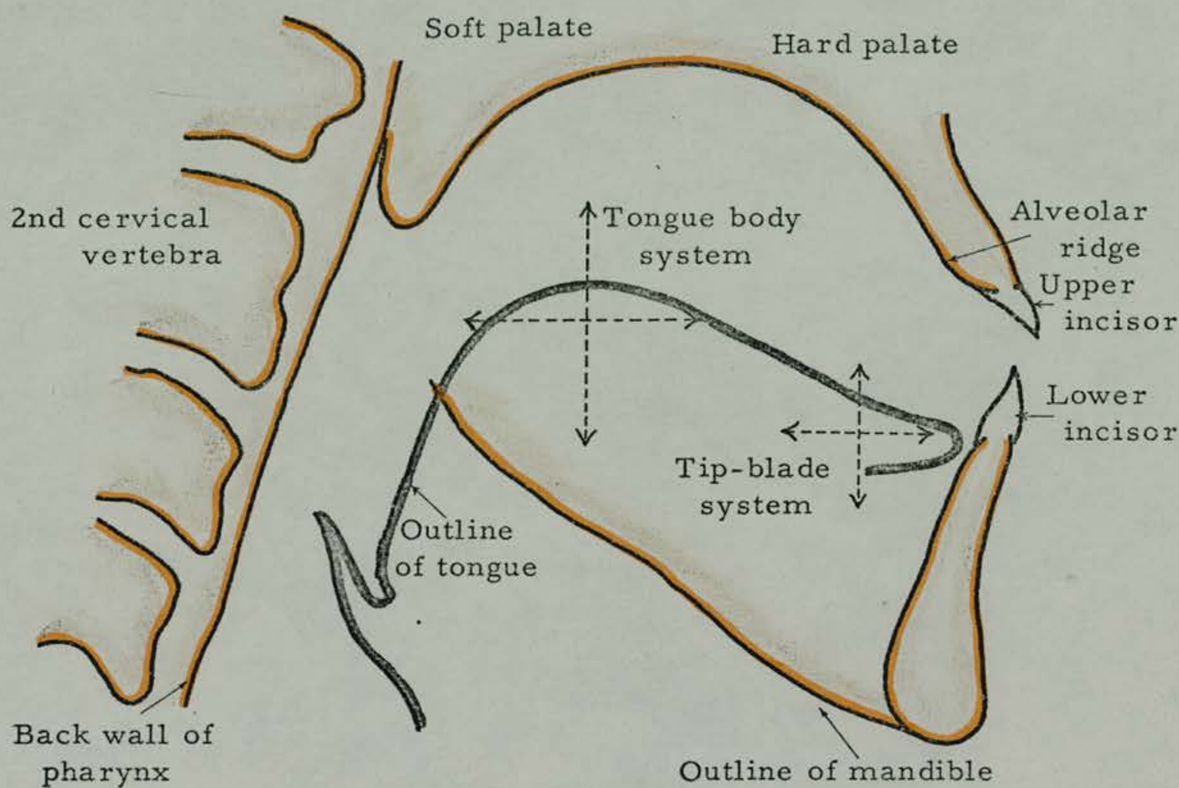
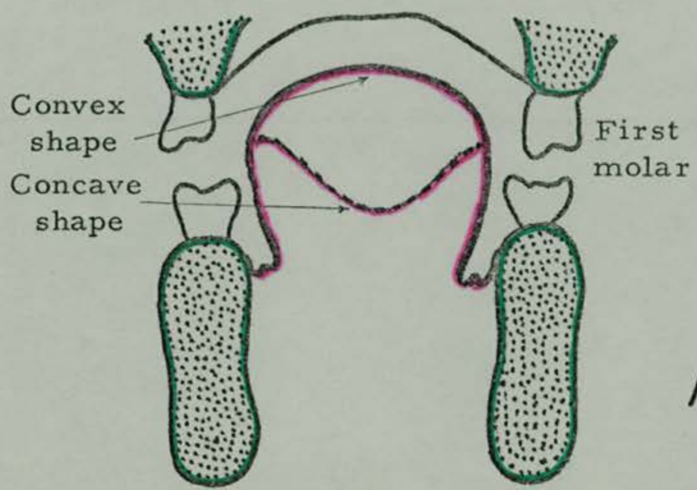
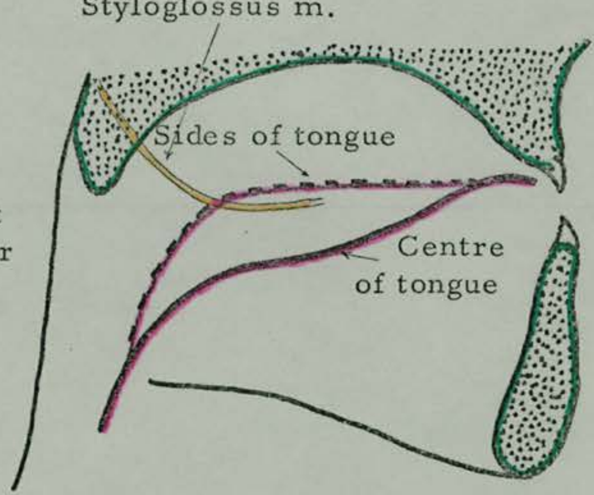


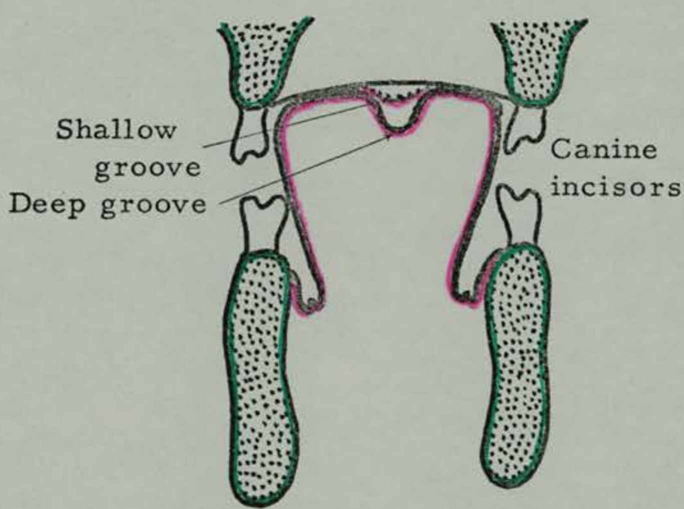
Fig. 24. Simplified tracing from an X-ray photograph during the articulation of [ə], showing the possible vertical and horizontal directions of movement of the tongue-body and tongue-tip/blade systems.



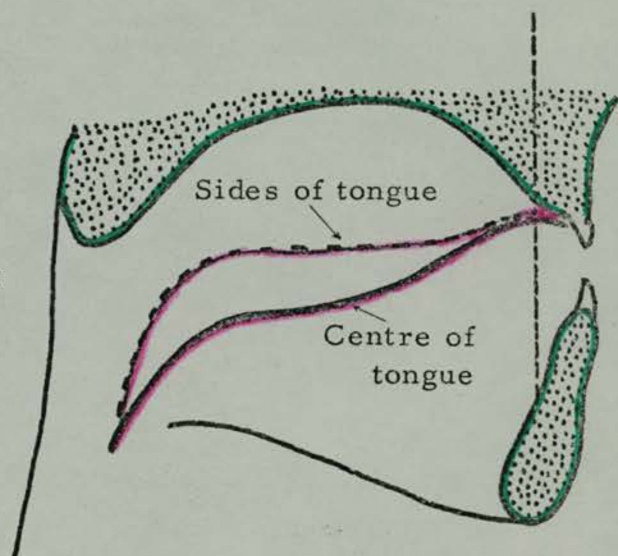
Parameter 5 : Convex-concave configuration



Sagittal section showing concave configuration



Parameter 6 : Degree of central grooving



Sagittal view showing plane through which section is taken

Fig. 25. Schematic diagrams illustrating tongue configurations utilizing articulatory parameters 5 and 6.

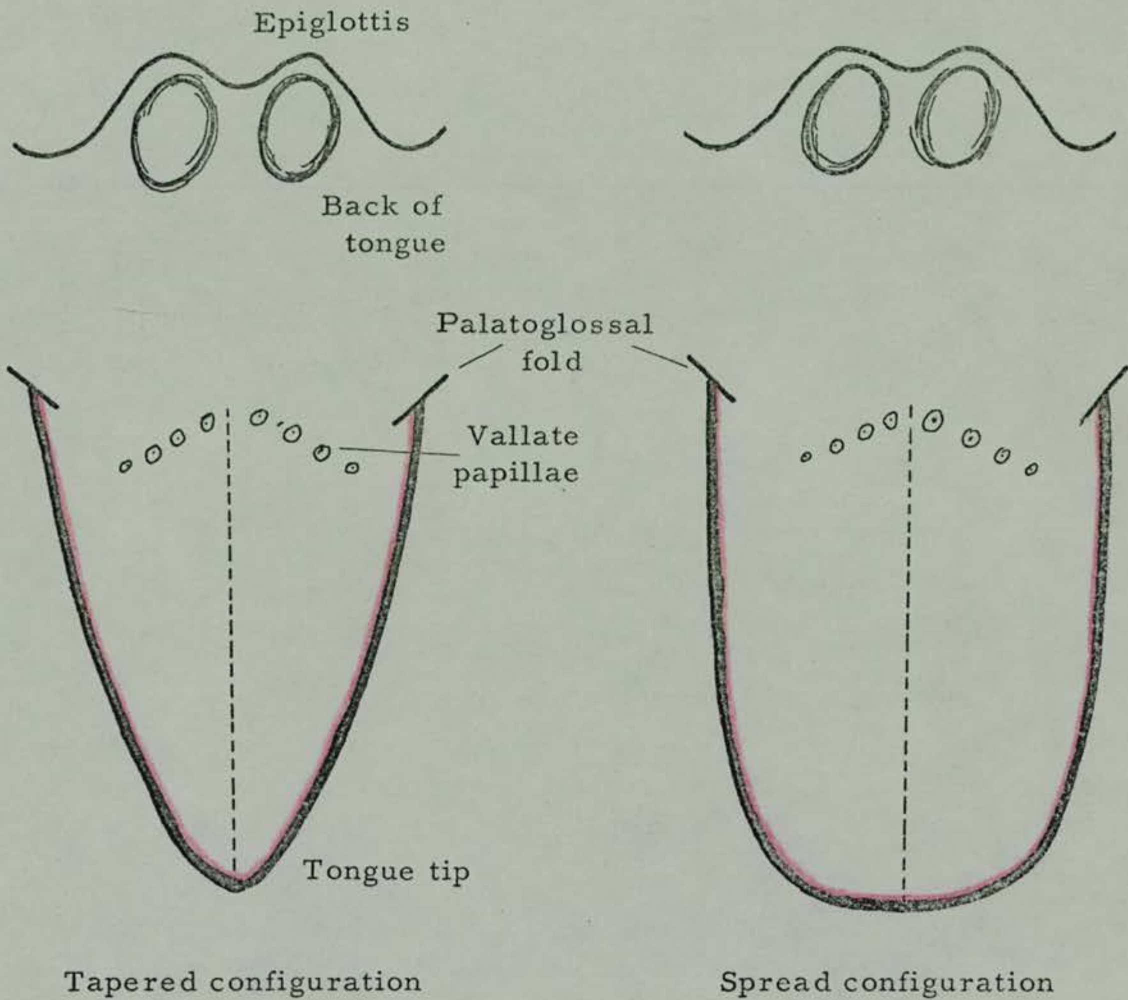


Fig. 26. Diagram of two different surface plans of the tongue utilizing articulatory parameter 7.

Different articulatory movements and configurations can be achieved by combinations of these seven basic parameters. Thus an oblique forward upward movement of the body and tip-blade system, with spread tongue configuration, such as would be appropriate for [t] would utilize a combination of parameters 1, 2, 3, 4 and 7. Some of the parameters may be irrelevant for certain articulations. Thus for low back vocoids parameters 3, 4, 5 and 6 are probably not necessary, the parameters chiefly involved being 1 and 2. In this case as far as parameters 3 and 4 are concerned, the tip-blade system does not act independently of the tongue body but is necessarily drawn along by any activity in the tongue body.

The muscular systems responsible for these seven parameters can now be specified. It must be emphasized here again that most of these statements to follow are highly speculative, in the absence of a comprehensive physiological model of lingual movement based on experimental evidence.

3.1. Tongue Body : Forward - Backward Movement

3.1.1. Forward Movement

The protagonist muscle for the forward movement of the tongue body is probably the posterior genioglossus (see Fig. 27). When contracting from a fixed mandible, it will draw the whole hyoid bone forward and upwards and thus the bulk of the tongue in roughly the same direction. The suprahyoid muscles, particularly the anterior suprahyoids including the geniohyoideus, mylohoideus, anterior belly of the digastricus and to a lesser extent the stylohyoideus, probably act in synergism from the fixed mandible (see Fig. 11, in Chapter 2, section 3). For the forward tongue movement, the hyoid is probably tilted forward slightly by a balanced contraction between the anterior infrahyoids (sternohyoideus and omohyoideus) and the stylohyoideus (see Fig. 11).

The forward movement may be important for some dental and alveolar articulations, for example [t̪] and [l]. The forward movement

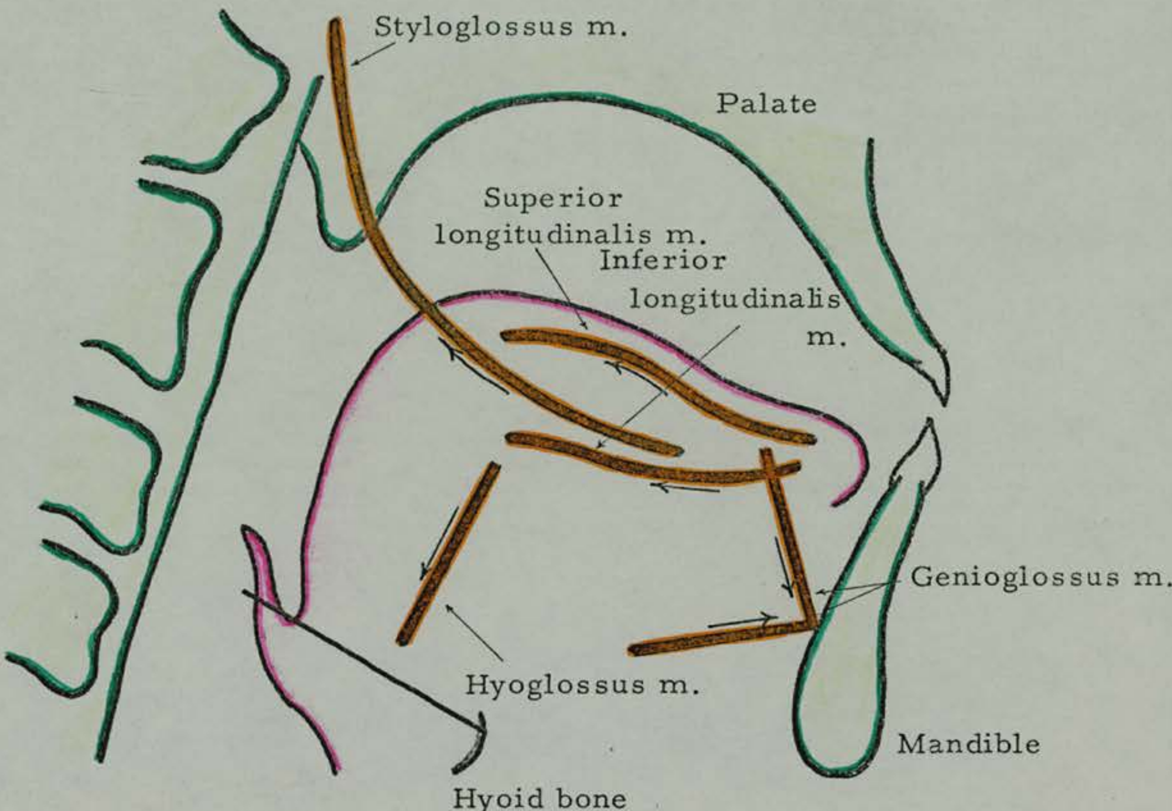


Fig. 27. Schematic diagram showing some of the tongue muscles contributing to the tongue body articulatory parameters illustrated in Fig. 24. The arrows indicate some of the possible directions of movement of the tongue when the muscles contract.

is usually combined with an upward tongue body movement (parameter 2).

3.1.2. Backward Movement

The horizontal backward movement of the tongue body is primarily accomplished by the styloglossus and constrictor pharyngis medius pulling back on the hyoid bone. Contraction of the styloglossus alone would draw the body up and back (see Fig. 27). The upward movement may be opposed by the thyrohyoideus pulling down on the cornu of the hyoid. The stylohyoideus and posterior belly of the digastricus probably act in synergism to the muscles pulling backwards (see Fig. 11, Chapter 2, section 3).

A horizontal backward movement of the tongue probably only occurs in pharyngeal articulations, for example Arabic [ħ] and also to some extent in low back vocoids such as [ɑ]. The backward movement, however, is frequently combined with an upward movement in the production of velar and uvular articulations such as [x], [χ], and backvocoids such as [u].

3.2. Tongue Body : Upward - Downward Movement

3.2.1. Upward Movement

The vertical upward movement of the tongue body is probably accomplished by the styloglossus and the palatoglossus (only if braced by levator and tensor muscles) with the inferior longitudinalis acting in synergism (see Fig. 27). These muscles acting as a group would probably tend to draw the tongue backwards as well. The backward movement may be opposed by the posterior fibres of the genioglossus.

The upward movement of the body may be important for some high central vocoids such as [ɨ] and for palatal contoids. In the production of a palatal stop complete occlusion of the tongue against the palate occurs. For this the tongue would have to assume a convex configuration in addition to the upward movement. Now, because the protagonists in the upward movement are the styloglossus and palatoglossus, which insert along the margins of the tongue, contraction of these muscles will tend to raise the sides making a convex configuration, and so the necessary closure, difficult. The sides of the tongue are probably drawn down by the action of the hyoglossus, the main depressor of the tongue, which also inserts along the margins (see Fig. 9, Chapter 2).

A similar configuration may be made for the vocoids. This will be discussed under section 3.5.2.

As mentioned earlier, the vertical upward movement may be combined with parameter I to produce an upward backward movement or an upward forward movement.

3.2.2. Downward Movement

The protagonist muscle in the downward movement of the tongue body is the hyoglossus muscle. This muscle inserts into the margins of the tongue so depresses the edges as well as the whole body. In lowering the tongue, the infrahyoid musculature consisting principally of the omohyoideus, sternohyoideus and the thyrohyoideus act synergistically (see Fig. 11). In addition, the intermediate fibres of the genioglossus may play some part in depressing the tongue body, particularly the centre of the tongue, when contracting from a fixed mandible (see Fig. 27).

The downward movement is particularly important for vocoid articulation where a balanced contraction between the elevators and depressors of the tongue is necessary to give the specific configuration appropriate for each vocoid. The downward movement would also be important for the release phase of most contoid articulations, for example stops and most fricatives. For alveolar articulation, however, the tip-blade parameters may be more functionally significant.

3.3. Tip-blade System : Forward-Backward Movement

The two parameters already discussed make use primarily of the extrinsic muscle system which, as was shown earlier (Chapter 2, section 3), is responsible mainly for gross positioning of the tongue body. The remaining parameters mainly utilize the intrinsic system although extrinsic muscles usually act in a synergistic capacity.

3.3.1. Forward Movement

Protrusion of the tongue tip is brought about primarily by intrinsic transversus muscle acting in synergism with the posterior genioglossus. This movement necessarily also involves parameter 1, using the forward tongue body movement.

Alveolar and dental articulations usually make use of the forward movement of the tip, depending on the environment. However, these articulations for some individuals often require an upward movement of the tongue. This will occur for instance if the tip lies relatively far forward in the mouth in the rest position.

3.3.2. Backward Movement

A backward movement of the tip is accomplished by both intrinsic longitudinal muscles (see Fig. 27). The superior longitudinalis tends to draw the tip up and back, while the inferior longitudinalis may actually depress the tip or bunch the whole body of the tongue back so retracting the tip. When both muscles contract together the net result may be a horizontal retraction of the tip "into" the body of the tongue. As seen earlier, the backward movement of the tip is important for retroflex articulations. Here the situation is rather complicated as the tip must also be extended slightly to facilitate the curled backward movement. At the same time as the tip moves backward, the body is depressed, probably by the hyoglossus muscle.

3.4. Tip-blade System : Upward-Downward Movement

3.4.1. Upward Movement

The protagonist muscle in raising the tip-blade system is the superior longitudinalis. This movement can be largely independent of tongue body movement so double articulations are possible. (The electropalatograph has shown an interesting variant in the writer's pronunciation of the final nasals such as in "singing". Simultaneous closure by the back of the tongue in the velar region and by the tip of the tongue in the alveolar region, is clearly demonstrated).

Upward movement by the tip is often accompanied by a general forward upward movement of the tongue body (parameters 1 and 2), for example approaching the closure phase of an alveolar stop [t] in the environment [a t i]. However, when the body is already positioned by the extrinsic musculature in a high front position (e. g. for [i]), the upward movement of the tip to produce an alveolar [t] is probably independent of the body movement and involves principally the contraction of superior longitudinalis.

Many other articulations, for example, fricatives such as [s], affricatives [tʃ], [t r] utilize this tip-blade parameter.

3.4.2. Downward Movement

The tip-blade system is depressed by both the inferior longitudinalis and the anterior genioglossus. As with the upward movement, in this movement the tip-blade system may act independently of the tongue body. Other times it can be kept neutral and carried about mechanically by the body system. The downward movement can be part of the release phase for alveolar articulations such as [t], [ɭ], [n]; it can also provide balanced control for the complex fricative [s]. Here it acts antagonistically with elevators such as superior longitudinalis, styloglossus and palatoglossus (when braced).

3.5. Transverse Cross-sectional Configuration : Concave-Convex (with Relation to the Palate).

3.5.1. Concave Configuration

The protagonist muscles contributing to a concave configuration are the styloglossus, palatoglossus and transversus. Because the insertion of the styloglossus is mainly in the posterior margins of the tongue and because this muscle is probably the largest and strongest of the three, the concave configuration occurs frequently in the posterior part of the tongue (see Fig. 25). A tracing from an x-ray photograph of [s], (see later, Fig. 28) shows clearly the wide concave configuration or sulcalization as it is sometimes called, in the back of the tongue.

The sulcalization is probably present to a lesser extent in some vocoids; however, the antagonistic effect of the hyoglossus would keep the margins of the tongue relatively depressed. The presence of this concave configuration particularly in the back part of the tongue for articulations such as [s] and [ʃ] has rarely been mentioned in the literature. It may, however, play an important role in producing the appropriate acoustic frequency associated with these configurations. The detailed physiology of the [s] articulation will be discussed in section 4.

3.5.2. Convex Configuration

The protagonist muscle for this configuration is probably the hyoglossus which inserts into the lateral margins. When contracting in conjunction with the inferior longitudinalis muscle, the resulting bulging back of the tongue will tend to have a convex configuration (see Fig. 25). This occurs usually for velar and palatal stops and fricatives and some high vocoids. As mentioned earlier, the tongue is positioned for vocoid articulation by the balanced contraction of the elevators (styloglossus, palatoglossus) and the depressors (hyoglossus, infrahyoid muscles). In some cases this may produce a convex configuration for the vocoid.

3.6. Transverse Cross-sectional Configuration : Degree of Central Grooving

The production of an accurately controlled groove requires the co-operation of many muscles. To a certain extent all the intrinsic muscles and certain of the extrinsic muscles play a part in this complex configuration.

The muscles probably most directly responsible for the groove are the median verticalis and transversus, particularly its superficial fibres (see Fig. 25, and Fig. 9, Chapter 2, section 9). The tongue may be spread out slightly by the whole verticalis. At the same time the styloglossus and palatoglossus (from a fixed soft palate) may act synergistically with the transversus in keeping the sides raised.

If the grooving occurs in the tip-blade system the central part of the tip is depressed probably by both the inferior longitudinalis and anterior genioglossus, which acts here from a fixed mandible. Antagonistic contraction of the superior longitudinalis would determine the depth of the groove, more tension probably creating a shallower groove (see Fig. 25).

The central grooving in the tip-blade system can probably be made more narrow and deep than in the posterior body of the tongue although there may be some sulcalization in the back part of the tongue due mainly to contraction of the styloglossus (see configuration for [s] in section 4).

The central groove is particularly important in the articulation of [s]. The "palato-alveolar" fricative [ʃ] in some individuals' articulation can perhaps be regarded as a "grooved" fricative, the groove here being wider and with shallower sides than for [s].

3. 7. Surface Plan Configuration of Tongue Dorsum : Spread or Tapered

3. 7. 1. Spread Configuration

This configuration is accomplished primarily by contraction of the verticalis muscle which tends to narrow the cross-sectional dimension and spread the tongue out sideways. As seen earlier (Chapter 2, section 3), the verticalis fibres are most dense towards the centre of the tongue and contraction of these median fibres may flatten the centre with respect to the sides (see Fig. 9). This configuration would be important for grooving (as described in section 3. 6.).

Spreading of the tongue surface may be important for stop articulation when the airflow is obstructed by the tongue articulating against the palate and teeth. Thus for an alveolar stop, e. g. [t] contact is seen on a palatogram as covering a horseshoe-shaped area of the palate including the alveolar ridge region and along both sides of the mouth on the gums. Similarly for other alveolar articulations such as

[s], the spreading action effectively seals off the sides of the oral air-way and directs the stream of air through the controlled central groove. For some vocoid articulation such as front vocoids [i], [e], considerable contact is seen along both sides of the palate up to the alveolar region. The tip is, however, lowered to allow the passage of air over the central line of the tongue.

3. 7. 2. Tapered Configuration

Narrowing of the tongue can be produced by contraction of the transversus muscle. As seen earlier, contraction of the superficial fibres of this muscle will tend to pull the sides inwards; this movement, however, may be opposed by action of the hyoglossus pulling down on the margins. If this occurs the tongue will not only be tapered but will have a convex configuration, particularly if the hyoglossus contraction is stronger than the transversus.

The tapering often accompanies a protrusion of the tongue or raising of the tip. When the tongue is protruded as it may be for instance in a dental articulation such as [l] by some speakers, the tapering of the tip may be accompanied by contraction of the posterior genioglossus acting from a fixed mandible.

The contraction of the transversus in producing the narrowed configuration most probably plays some part in lateral articulations, where the airstream is obstructed in the centre of the vocal tract but allowed to escape round one or both sides of the obstruction.

4. ARTICULATION OF THE COMPLEX FRICATIVE [s]

Using these seven articulatory parameters, each on a scalar basis, it is possible to give an approximate specification of the majority of the different lingual motions and configurations used in speech. We have seen in the above sections that a correlation can be drawn between a given articulatory parameter and its probable underlying physiological mechanism. However, before any really comprehensive theory of linguistic performance could be achieved at the phonetic level, it should be possible to allocate quantitative values not only to the articulatory parameters of a given articulation, but also to the individual contribution of the muscles and muscle systems participating in the articulation. Thanks to various instrumental techniques, we can begin to quantify the parametric articulatory values of speech events, but reliable quantification of the muscular contributions is a very long way ahead at the moment, given the current inefficiency of such techniques as electromyography. What we can do at the moment is to attempt better quantification of articulatory parameters, with the help of techniques such as electropalatography, and if not quantify the muscular contributions, at least try to identify, theoretically, the muscles involved in particular articulations. As an example of this approach to the fringes of a physiological theory of phonetics, it may be interesting to look in detail, as an example, at the articulation of the voiceless grooved alveolar fricative [s], and speculate about its articulatory and physiological make-up.

It has been mentioned earlier that [s] can be regarded as a "complex" fricative requiring maximum delicacy both of muscular control and sensory feedback for its production. Just what "complexity" means in terms of physiological mechanisms can be illustrated by a detailed description of this articulation, in terms of the seven parameters.

The production of [s] in the environment [əsə] is considered. The three phases of the articulation are described :- the <u>approach</u> to the position, the <u>hold</u> phase, where a specific tongue configuration is maintained during the production of the turbulence in the air-stream and the <u>release</u> phase where the tongue returns to the [ə] position.

4.1. <u>The Approach Phase</u>

From the position for [ə], the whole tongue body moves forward and upwards towards the alveolar region, by the combined effort of posterior genioglossus, styloglossus and palatoglossus (parameters 1 and 2). As the tongue moves forward a concave configuration forms in the body of the tongue due mainly to contraction of styloglossus and palatoglossus (parameter 5). At the same time also the tip-blade system is beginning to form the central groove (parameter 6) by contraction mainly to the median verticalis and superficial transversus muscles.

Simultaneously with the forward movement of the tongue body, the mandible moves slightly forward and upwards. The mandibular elevators including the temporalis, masseter, internal pterygoideus and possibly also the external pterygoideus (see Chapter 2, section 3) are mainly responsible for this movement.

4.2. <u>The Hold Phase</u>

The specific configuration for [s], involving a central groove in the tip-blade system while the sides of the tongue are held firmly against the lateral dentition is extremely complex and requires the concerted activity of many muscular systems. Fig. 28 shows an x-ray tracing of the tongue configuration for the hold phase. (The x-ray lateral view of the head was shot from a distance of 6 ft. with exposure time of 1.5 sec. at 100 mA and 70 kil. V.).

The formation of a central groove has already been outlined above (parameter 6). For the production of [s], the groove is maintained primarily in the tip-blade system by the balanced contraction of both extrinsic and intrinsic muscles. The protagonist muscles are probably the median verticalis and superior transversus with the inferior longitudinalis acting synergistically to lower the tip. Contraction by the verticalis muscle probably contributes to the lateral spreading of the blade (parameter 7). Balanced contraction by the superior longitudinalis and anterior genioglossus ensures the tip is lowered to just the right degree to allow the airstream to pass out of the central groove.

At the same time as the central groove is being maintained, the whole tongue body is moved forward in the mouth, chiefly by the protagonist activity of the posterior genioglossus (parameter 1). The anterior suprahyoid muscles probably act synergistically in this movement, the mandible meanwhile being fixed by the elevators. To

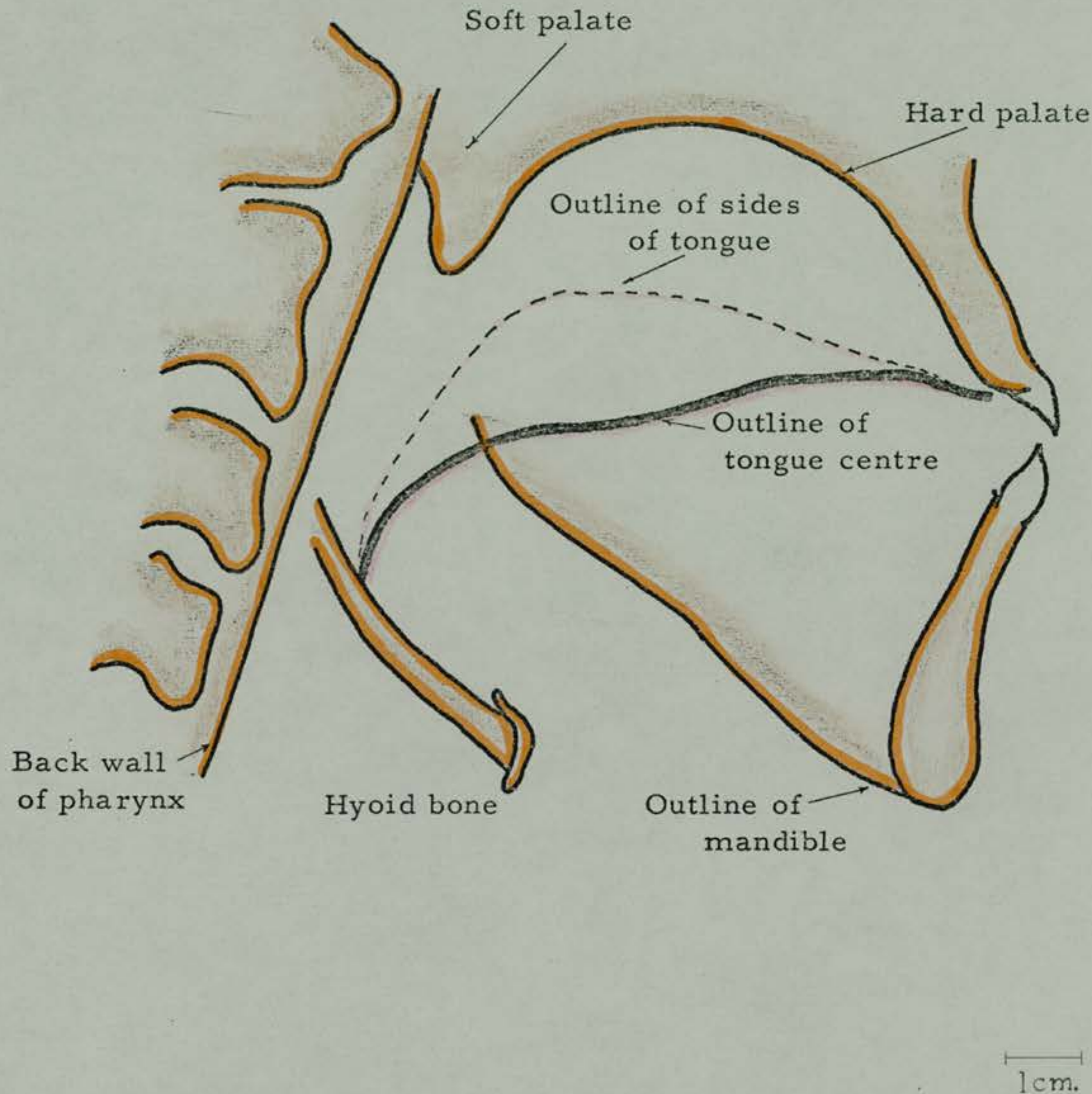


Fig. 28. Simplified tracing from an X-ray photograph taken during the articulation of [s]. The dotted line represents the raised sides of the tongue forming a sulcalized configuration.

prevent the tongue moving forward too far in the mouth, the depressors of the tongue, the hyoglossus and the infrahyoid musculature probably contract antagonistically.

It was mentioned above that the styloglossus and palatoglossus (acting from a fixed velum) contribute to the forward upward movement of the body and because the muscles are inserted along the lateral margins of the tongue the back part forms a concave or sulcalized configuration (parameter 5). The x-ray tracing (Fig. 28) shows this sulcalization clearly.

Articulation of [s] depends probably to a large extent on the precise control of the anterior central groove. Just the right amount of balanced tension must be exerted by the superior longitudinalis and anterior genioglossus to lower the central part of the tip sufficiently to allow the air to pass. There is thus a mutual dependency of air-flow, orifice size and pressure ratio (This type of dependency has been measured by investigators such as Warren and Du Bois, 1964, using hydrokinetic formulae). The sustained balanced contraction is necessary throughout the critical hold phase.

The mandible is fixed by contraction of the masseter, temporalis and internal pterygoideus muscles acting antagonistically with the depressors of the mandible such as the anterior suprahyoids.

4.3. Release Phase

Both the body and tip-blade systems are lowered and slightly retracted mainly by the hyoglossus and inferior infrahyoids (parameters 1 to 4), for the release. The mandible is lowered by the anterior suprahyoid musculature.

4.4. Fricative [s] as a "Complex" Articulation

We can see from this description that [s] makes use of all seven parameters. What makes the articulation particularly complex, however, is that not only are all the parameters utilized at some stage in the articulation, but very delicate control takes place for each parameter.

Not all articulations utilize these parameters to the same extent as [s]. Thus most vocoids, for example, probably only involve parameters 1, 2 and possibly 3, 4, and 5. It can be said then that, in a sense, some articulations are more complex than others, with "complexity" being defined in terms of the number of parameters active and the delicacy of control exerted on those parameters by their underlying physiological mechanisms. In general, complex articulations would involve a greater number of the seven articulatory parameters than less complex articulations; however, each parameter probably doesn't require the same degree of physiological control. Thus, for example, parameters 1 and 2, involving gross movement of the tongue body probably don't employ such delicately controlled physiological mechanisms as degrees of central grooving of the tip-blade system (parameter 6). It may perhaps be possible to weight different parameters according to their place in a hierarchy of degrees of physiological delicacy required for their production. To a certain extent, this is already possible by regarding those parameters primarily involved in activity of the extrinsic muscle system of the tongue as being less complex than those requiring contribution from both the extrinsic and intrinsic systems.

Adopting a parametric approach such as that described above, we can, at least in theory, perhaps arrange all sounds in a cline from simple to complex articulations; the complex exhibiting maximally delicate interrelationships between both the articulatory parameters and physiological mechanisms.

This concept of complexity may have applications throughout nearly all sciences involved with speech. For example, a parametric approach specifying not only precisely defined articulatory parameters but also physiological mechanisms underlying them may be more suitable as a unifying theory behind speech acquisition. It is possible that children, in acquiring speech, progress from simple to complex articulations; i.e. they acquire more and more interrelationships between different parameters. This sort of parametric approach also may be more applicable in explaining certain aspects of historical sound change:

it may be possible, for instance, to posit a general tendency in a given language for sounds to change throughout time from more complex to more simple articulations. Such a theory would provide an interesting parallel to the general simplification of grammar during the Middle English period where the once declinable final "e" became an unstressed "schwa" type articulation, until it was finally omitted altogether.

The concept may also have important applications in formulating theories of language universals. It may be shown, for example, that the complex articulations occurring in any language are more likely to be produced in the front part of the oral region involving primarily the anterior part of the tongue, because the physiological constraints are such that it is only this part of the tongue that is capable of exploiting the wide range of delicately controlled articulatory parameters required in complex articulation.

Another reason why most complex articulations seem to occur in the anterior oral region is that this is precisely that region best endowed with sensory exteroreceptors and proprioceptors (see Chapter 2, section 1). It seems plausible to assume that the tactile and proprioceptive feedback systems assist in controlling the accurate production of these complex articulations.

The distribution of sensory receptors in the oral region,particularly in the tongue, and the observation of the place of articulation of most English complex articulations, suggest that there is a direct relationship between complexity of articulation as defined above and density and variety of sensory mechanisms involved in any given articulation. This hypothesis will be examined more closely in the following chapter.

5. SUMMARY

To sum up, therefore, this chapter has been an attempt to indicate the direction which a formulation of a comprehensive phonetic theory should take. Rather than specify in a general fashion, as is the practice in conventional phonetic theory, articulatory parameters such as place and manner for articulations such as [s], an attempt has been made here to specify not only the intersection of detailed articulatory parameters, but also to indicate the physiological mechanisms underlying these parameters. Phonetic articulatory parameters have been modified to make them more precise, and to try to relate them more simply to the physiological parameters they employ.

The next chapter will investigate experimentally the role of sensory feedback in myodynamic control of different articulations, particularly complex articulations, such as [s] and [ʃ].

CHAPTER 6

THE ROLE OF SENSORY FEEDBACK IN THE MYODYNAMIC CONTROL OF SOME ASPECTS OF SPEECH PRODUCTION

INTRODUCTION

In Chapter 2, the different types of sensory resources in the oral region and their importance in providing sensory feedback information to the C.N.S. were discussed at some length. It was seen how the intricate neural mechanisms of the tongue, comprising different types of sensory receptors in the epithelium, papillary and sub-papillary lamina propria and in the muscles themselves, provide the C.N.S. with continuous detailed sensory information, which is presumably utilized inthe control of myodynamic performance for speech production. As the discussion in Chapter 5 indicated, this type of sensory control is probably of great importance in the sensori-motor co-ordination of complex articulations particularly those involving articulation of the anterior region of the tongue against the palate. In order to investigate the role of various types of sensory feedback systems involved in some aspects of speech production, particularly in the place of articulation of complex articulations, an experiment was undertaken involving controlled interference with the normal sensory feedback channels. This type of experiment (which will be discussed at length in this Chapter) is a good example of the sort of investigation in which the technique of electropalatography can be used as an analytic technique to provide quantitative data concerning temporal and spatial factors of tongue-palate contacts. The particular importance of electropalatography lies in the fact that the relevant data cannot be obtained by any other instrumental techniques at present (see Chapter 3).

As indicated earlier (Chapter 2), there are three main types of feedback circuits used for myodynamic control in speech:- auditory feedback, reporting on bone and air sound-conduction in the ears; tactile feedback, reporting on touch and pressure arising from contacts between different oral structures; and proprioceptive feedback, reporting on tension in the muscles and movement of the joints. The aim of this experiment is to alter each of these different feedback systems under controlled conditions by affecting the relevant sensory receptors and observing the effect of these sensory alterations on different aspects of speech production, using instrumental techniques such as electropalatography and sound spectrography. The basic design of the experiment implies, of course, that it is possible to alter these different types of sensory feedback sufficiently to produce some measurable alterations in speech performance. This is possible to varying degrees: auditory feedback can be diminished by high-amplitude white noise masking; and both tactile and possibly proprioceptive feedback (see below section 1.2.) can be affected by various anaesthetic techniques. The effect of these different experimental conditions on speech production can be measured and some inferences can be made from the results about the possible roles sensory feedback systems play in the speech monitoring process. The results can then be analysed in the wider context of their implications for models of speech performance.

In most investigations of this type by phoneticians there has been considerable disagreement concerning the effects that anaesthetic and masking techniques have on sensory feedback. A brief review of the previous experiments will illustrate some of the sources of disagreement.

1. REVIEW OF PERTINENT LITERATURE

A number of investigations have been carried out examining the contribution of sensory feedback mechanisms in the control of myodynamic performance for speech production. Most of these experiments have been confined to altering auditory feedback either by delayed auditory feedback techniques (e.g. Black, 1951; Fairbanks, 1955; Fairbanks and Guttman, 1958; Huggins, 1967) or by various levels of white noise masking (e.g. Lightfoot and Morrill, 1948; Hanley and Steer, 1949; Fry, 1954; Ham, 1957; Schwarz, 1968; Charlip and Burk, 1969; Brown and Brandt, 1970).

The most commented-upon effects of alterations in auditory feedback have been, in general, increased vocal intensity, increased intraoral air pressure, longer duration of articulation, higher fundamental frequency and general "articulatory inaccuracy."

Relatively fewer investigations have been carried out to assess the role of the tactile and proprioceptive types of feedback in speech production. Tactile feedback has been altered by both application of topical anaesthetic and also by anaesthesia of the lingual nerve by injection (e.g. Guttman, 1954; McCroskey, 1956, 1958; Weber, 1961, Ringel and Steer, 1963; Ladefoged, 1967 (a); Weiss, 1969). Most of these investigations also examined the effect of disrupted auditory feedback either alone or together with the anaesthesia. The conventional method of anaesthetizing the surface of the oral structures is by applying xylocaine HCl solution (usually between 5-10% concentration) to the surface of the oral mucosa by means of a cotton swab (e.g. Weiss, 1969), amethocaine hydrochloride lozengers (Ladefoged, 1967 a) by spraying, using an aerosal pack, or by some combination of these procedures such as spraying and swabbing. These anaesthetic procedures were assumed, without quantitative test procedures, to result in tactile sense deprivation (Ringel and Steer, 1963 : 371). In addition to the topical anaesthesia, some investigators also injected a 2% xylocaine solution into a region close to the mandibular nerve (with its branches the lingual and inferior alveolar nerve) (e.g. Guttman, 1954; McCroskey, 1958; Weber, 1961; Ringel and Steer, 1963). The procedure of hypodermic nerve anaesthesia, or nerve "block", was described by McCroskey (1958) thus:

"Bilateral mandibular blocks of the inferior alveolar nerves at the mandibular foramen were performed in standard manner. The lingual and buccal nerves were anaesthetized with the same injection at different depths of needle insertion. The buccal nerve is located just beneath the surface of the mucosa at the apex of the retromolar triangle, while the lingual nerve is medial and anterior to the inferior alveolar at the level of the mandibular foramen. Anaesthesia of these three pairs of nerves eliminated sensory innervation to the lower lip and cheek, the buccal and lingual gingivae, and the anterior two-thirds of the tongue as well as the entire alveolus and teeth. The upper lip was anaesthetized by infra-orbital foramen injections from an intra-oral approach" (p. 85).

Most investigators assumed that under lingual block conditions, sensory reception in the front part of the tongue (presumably tactile and perhaps proprioceptive) was greatly affected if not eliminated entirely. Thus McCroskey (1958 : 85) claims that lingual block "eliminated" sensory innervation to the anterior two-thirds of the tongue and Ringel and Steer (1963 : 370) state it resulted in "severe alterations within the tactile feedback channel." McCroskey's statement suggests that lingual block is assumed to eliminate proprioceptive as well as tactile feedback. This suggestion is echoed by Ladefoged (1967a) who, in discussing the experiment by Ringel and Steer, states that subjects will "be at least partially deprived of kinesthetic[1] as well as tactile feedback from the tongue by anaesthetizing the fifth cranial nerve, which carries the sensory impulses from these muscles" (p. 165). The sensory innervation of muscle receptors such as spindles which provide proprioceptive feedback information, is, however, an extremely controversial subject (see Chapter 2, section 1. 3. 2.) and, as we shall see later, it is by no means established that the sensory endings of spindles in the tongue are supplied by the lingual nerve branch of the fifth cranial complex.

Of all the experiments investigating the effect of disrupted tactile feedback on speech production, that of Ringel and Steer is probably the most carefully controlled so will be discussed at some length here. Where relevant, their results will be compared with those of other investigators.

1 "Kinesthetic" and "proprioceptive" have been used by different writers in different ways. Kinesthetic as a general term usually refers to the "sense of movement" and probably involves the integration of both tactile and proprioceptive feedback. Ladefoged's use of kinesthetic to denote that type of feedback providing information concerning "stretch of the muscles and movement of the joints" (1967 a : 163) is exactly equivalent to the term proprioceptive used in this research.

For their experiment, Ringel and Steer analysed four speech variables, "articulation", "duration", "average peak level" and fundamental frequency, of thirteen subjects under the following experimental conditions:

(1) Control (i.e. normal condition).

(2) With binaural masking noise (94db in both ears).

(3) With topical anaesthetic (4% xylocaine HCl applied by spraying and swabbing to the surface of the oral mucosa).

(4) With mandibular block anaesthesia (i.e. injecting 2% xylocaine HCl close to the lingual infra-orbital nerves, using the technique described by McCroskey (1958), quoted above.

(5) With topical anaesthesia and binaural masking noise.

(6) With mandibular block anaesthesia and binaural masking noise.

The subjects recorded a sentence "years later boilers and engines were invented and sailors could strike their enemies at will," and the following measurements were taken : (1) average amplitude peak levels, measured from a high-speed level recorder (2) mean fundamental frequency values determined through analysis of tracings from photographs of the speech wave form as projected on an oscilloscope. Measurements were also made of mean syllable duration, overall word-per-minute rate and phonation/time ratio on a longer experimental reading passage. The subjects' articulation performance was "judged" by a panel of four judges.

In their summary, the authors stated, "In general, under conditions of nerve block anaesthesia, speech is characterized by significant increments in amplitude of performance, lack of rate variability, and articulatory inaccuracy. Finally, it is reported that 'for certain speech output variables, the effects of multiple sensory disturbances are cumulative in nature." The authors' finding that the condition of bilateral lingual block anaesthesia resulted in more articulation errors than occurred during a condition of normal feedback agreed with other investigators (e.g. Guttman, 1954, McCroskey, 1958, Weber, 1961). In addition, Ringel and Steer found no significant effect on articulation under topical anaesthesia conditions, thus agreeing substantially with Weiss (1969). They also noted, as did McCroskey (1958) that "intelligibility" was found to be lessened more by interference with tactile cues than by disruption of auditory feedback. It may, however, be more correct to say as Ladefoged did (1967 a), that different types of articulation rely on different types of sensory feedback control. His conclusions were based on the results of an informal experiment he carried out involving articulation of various vowels and consonants under three experimental conditions - normal, topical anaesthesia and auditory masking. His results suggested an hypothesis that "vowel quality, nasality and pitch, are most simply related to an ordering of the acoustic properties of the stimulus, whereas most consonant qualities and features such as stress, are ordered more simply in terms of articulatory activity." (p. 165) These results and those of McCroskey (1958) mentioned above, incidentally seem to refute Fry's (1957) claim that "the two main (feedback) circuits are the auditory and kinesthetic....." (see Chapter 2, section 1.3.2.1.).

There are three fundamental limitations in all the studies mentioned above, investigating the role of feedback in speech production.

(1) No suitable experimental methods were used to quantify the speech performance data, particularly the articulatory data.

(2) None of the studies were based adequately on rigorous physiological and anatomical frameworks for investigations of this type.

(3) No attempt was made to assess the degree of attenuation that selective anaesthesia had on the sensitivity of sensory reception.

These limitations, and the steps taken in this research to avoid them are now discussed in some detail.

1.1. Experimental Techniques for Quantifying Speech Performance Data

One of the most interesting results from the above experiments involving alterations to the different sensory feedback systems was that lingual block anaesthesia caused "articulatory inaccuracy." This was noted, for instance, by Ringel and Steer (1963 : 371) who based their results on articulation judgments made by a panel of four judges "who were instructed to evaluate the recordings with respect to articulation as critically as possible and to indicate the number of articulatory deviations present in each recording." The only result of this "test" was that significantly more articulatory errors were said to occur in the presence of nerve block conditions than under any of the other experimental conditions. Using this sort of evaluation, however, no details could be obtained concerning the precise nature of these so-called errors of articulation. McCroskey (1958) and Weber (1961) in their experiments use similar approaches, relying on panels of listeners for articulatory judgments. Weber (1961), however, in his anaesthesia experiment does provide a few more details as to the nature of the articulatory errors; he divides them up into "distortions, substitutions and omissions." He found that most errors under the combination condition of nerve block together with auditory masking were distortions, although no details are given as to the articulatory characteristics of these distortions. Ladefoged (1967 a) gives no details at all as to what methods he used to examine his data.

Most of these studies thus relied on subjective responses either of the experimenter himself or of a panel of judges. Clearly, instrumental methods for providing objective, quantitative data on different aspects of speech production which could then be correlated with auditory impressions, are preferable in future investigations of this type. Electropalatography thus plays a central role in the present experiment, by providing detailed information on a number of articulatory features including temporal and spatial aspects of tongue contacts with the palate.

1.2. Adequacy of Physiological Framework for Investigations

Anaesthetic techniques, while quite common as research tools in physiology, have not in the past been frequently associated with phonetic research. This is because quite specialized knowledge is required for using the techniques which alter tactile and proprioceptive sensation.

Up until now, no suitable physiological framework for research of this type has been readily available to phoneticians. This has meant that most phoneticians undertaking research involving interference with sensory reception have been unable

(a) to design adequately rigorous experiments,

(b) to assess the likely effects that anaesthetic techniques will have on sensory receptors, and

(c) to interpret their results in the context of a plausible physiological model of speech performance.

The discussion in Chapter 2 was an attempt to collate relevant anatomical and physiological information from a wide variety of sources in order to provide a framework which, it is hoped, could be considered adequate for this type of research.

One of the main areas of confusion in previous investigations has been to determine or at least hypothesize, the degree of diffusion of topical anaesthetic and lingual block anaesthetic in the tongue and other oral structures. As far as topical anaesthetic is concerned, it seems probable that it does not penetrate much below the papillary lamina propria and almost certainly does not reach the muscle fibres (Sprinz, 1970; Slessor, 1970). It is probable, therefore, that the superficial free endings are affected by the topical anaesthetic but not the organized endings situated deep in the sub-papillary lamina propria or the muscle spindles in the fibres (see Chapter 2, section 1.2.2.). One could expect, therefore, tactile feedback but not proprioceptive to be affected by topical anaesthesia. This is, of course, extremely hypothetical, in the absence of any physiological experimentation on the degree of diffusion of topical anaesthetic. It is, however, based on a careful review of the histological research on the structure and distribution of sensory resources in the tongue (see Chapter 2, section 1.2.2.). Such considerations do not appear to have been observed in the other experiments mentioned above.

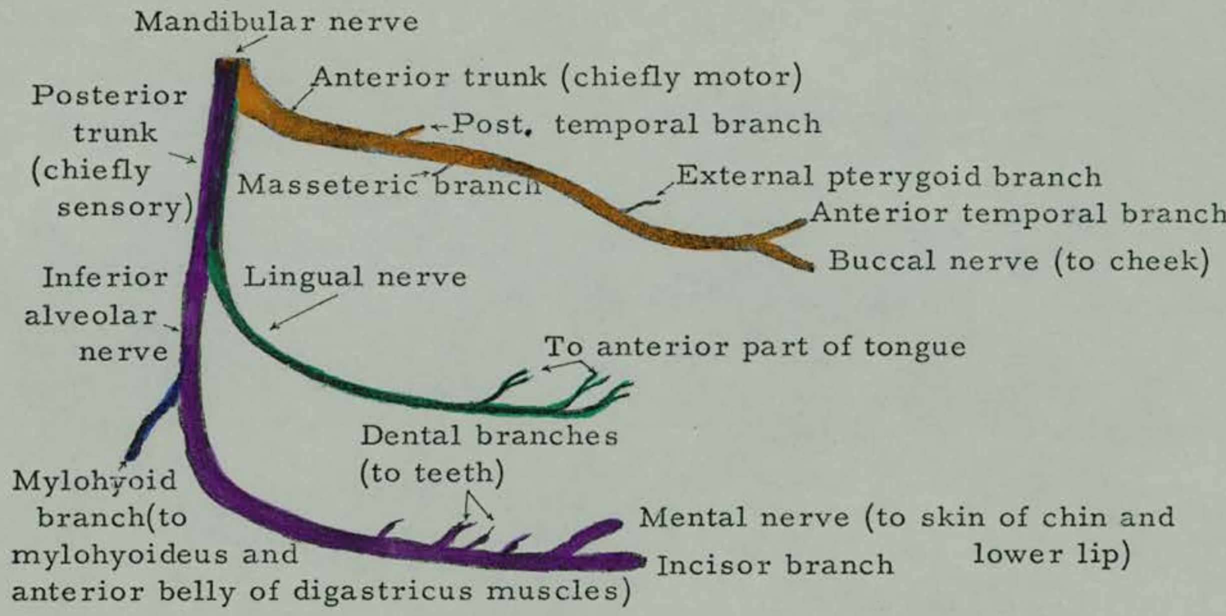
As far as the effect of lingual block on particular sensory receptors and consequent feedback control is concerned, the situation is even more complex. Fig. 29 shows the course of the lingual and inferior alveolar nerve branches of the mandibular nerve and the usual area of injection of the anaesthetic in a lingual block. As mentioned in Chapter 2, the lingual nerve supplies tactile sensations other than taste for the front two-thirds of the tongue. One can reasonably hypothesize that the lingual block would affect the tactile resources in the front two-thirds, including the free-endings and probably also the deeper organized endings, such as Meissner corpuscles, Krause end-bulbs, etc. The questions as to whether the lingual nerve supplies the sensory endings from muscle spindles contributing to proprioceptive feedback is difficult to answer at present. As we saw in Chapter 2 (section 1.3.2.) there are three possible afferent routes for the sensory endings from the spindles in the tongue:

(1) the lingual nerve,

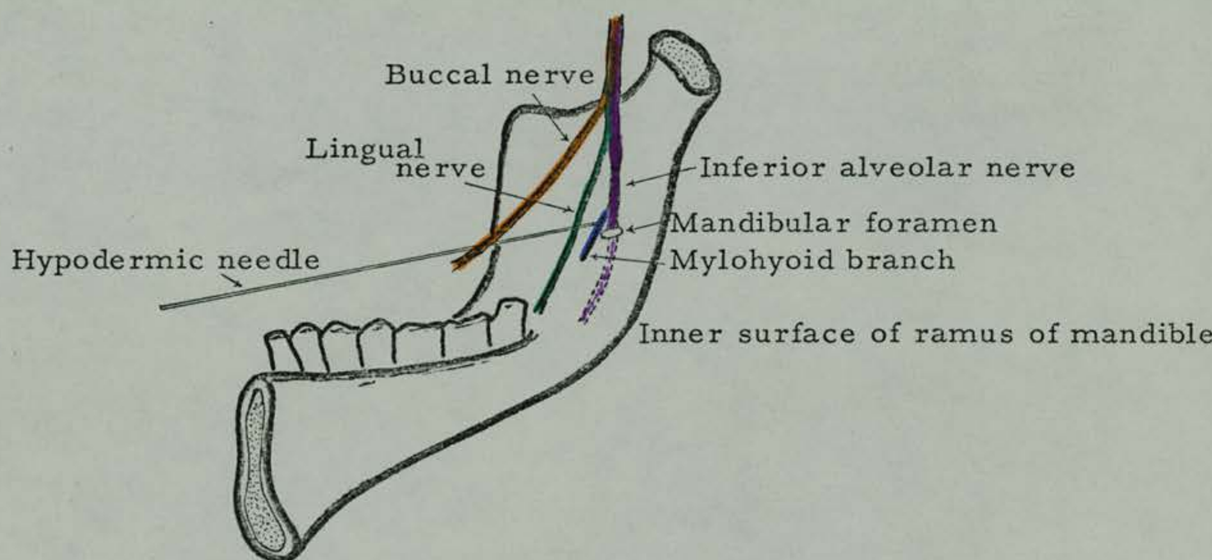
(2) the hypoglossal nerve, which supplies motor innervation to the tongue, or

(3) some of the cervical nerves and possibly the autonomic nervous system.

Favouring the hypoglossal pathway as a likely route, Cooper (1953) stated, "The intrinsic muscles of the tongue receive their motor innervation from the hypoglossal nerve. This nerve may therefore carry the afferent impulses from the muscles..... In man, Pearson (1945) has shown that there are numerous sensory type cells belonging to the hypoglossal nerve and having an intramedullary position near the inferior olive. These may well be the cells of origin of the muscle spindle sensory endings in the human tongue" (p. 199).



(A) Scheme of distribution of mandibular nerve



(B) View of inner surface of mandible showing approximate position of mandibular nerve branches

Fig. 29. Diagrams showing (A), the main branches of the mandibular nerve and (B), the approximate point of insertion of the hypodermic needle for a lingual block. The juxtaposition of the inferior alveolar, lingual and buccal branches of the mandibular nerve can be clearly seen from diagram (B). (after Cunningham, (1964), and Monheim, (1961)).

Much more research is still needed before we can state with any degree of confidence that "blocking" a particular nerve with anaesthetic solution necessarily has an effect on proprioceptive feedback. It is certainly premature to claim as Ladefoged (1967 a) has done when discussing the experiment by Ringel and Steer, that subjects will be at least partially deprived of kinesthetic as well as tactile feedback from the tongue, by anaesthetizing the fifth cranial nerve, or to assert blandly as McCroskey (1958) has done "that lingual block eliminated all sensory reception in the tongue." (p. 85). It is not even certain that lingual block will affect all the free endings and organized endings above the level of muscle fibres in the tongue. The only way to be certain of this would be to sever the lingual nerve, which would be clearly unacceptable.

1.3. Sensory Deprivation Testing Procedures

Most of the experiments mentioned above to investigate the role of tactile feedback in speech production using lingual block or topical anaesthetic techniques, include some brief comment as to the likely effect on the tactile feedback channel by the anaesthesia. Ringel and Steer (1963 : 370) thus claim topical xylocaine resulted in "minimal interference with tactile feedback" and lingual block resulted in "severe" alterations to the tactile feedback channel. This is clearly an hypothesis, which, as far as one can tell from the description of the experiment, was not tested quantitatively in any way. Weiss (1969 : 16) makes reference to a "pointed probe" test carried out presumably to determine if the topical anaesthetic was having any effect on tactile acuity in the tongue. Once again, here no attempt is made to quantify the sensory deprivation under any controlled experimental conditions.

In the present experiment, it was decided to avoid this limitation by including some testing procedure to quantify the relative attenuation that selective anaesthesia and auditory masking had on the sensitivity of sensory reception. Various standard tests were considered, including two-point discrimination tests (e.g. Ringel and Ewanowski, 1965 ; Grossman, 1967), oral stereognosis tests (e.g.

Baker, 1967; Shelton et. al., 1967), vibro-tactile tests (e. g. Neilson et. al. 1969) electrical stimulation tests (e. g. Grossman, 1967) and a number of tests designed to measure force-thresholds for applied stimuli (e. g. Grossman, Hattis and Ringel, 1965; Grossman, 1967). As this experiment is concerned with examining the effect of sensory deprivation on various aspects of speech production, it was thought desirable to select a test which would attempt to quantify the type of sensory discriminations most plausibly involved in speech articulation. As it was clearly demonstrated that different parts of the tongue touched the palate during production of [s], it seemed plausible to assume that some sort of easily quantifiable force-threshold test would provide the most appropriate data. As there seemed to be no suitable instruments available commercially for use within the oral region, a testing device was constructed in the Phonetics Laboratory which could assess the force-threshold for an applied stimulus to the tongue surface under different experimental conditions. A description of the experimental device and the testing procedure used,is included below in section 3.5.

At all times care was taken in the present experiment to control the experimental conditions as closely as possible for research of this type and to avoid as many as possible of the limitations of previous similar investigations.

As it was somewhat uncertain what sort of effects one would expect under lingual block conditions, a pilot experiment was carried out before the main experiment. It was important also to make a preliminary exploration of the feasibility of using electropalatography in providing some of the quantitative data on the place of articulation and timing. It was also intended that the results of the pilot experiment would generate some general hypotheses which could be tested in the main experiment.

2. OUTLINE OF PILOT EXPERIMENT

2.1. Experimental Procedure

In the pilot experiment two experimental conditions were used; -

normal i.e. absence of any experimentally induced disturbance of feedback, and bilateral lingual block i.e. anaesthetization of the lingual and inferior alveolar nerves using conventional dental techniques (see McCroskey, 1958, and above, section 1.) During the recording for both experimental conditions, the subject wore the artificial palate (type 1 in Fig. 19) connected to the electropalatograph (see Chapter 4).

Tape-recordings were made of the subject reading a number of passages containing instances of the fricatives [s] and [ʃ] in different environments during both experimental conditions - the normal and bilateral lingual block. The passages included the sentences "She can try to shelter with Esther in the cool dry German church on the quay"; "She had a sieve of sifted thistles"; "She sells sea shells on the sea-shore; the shells that she sells are sea shells I'm sure", and a number of words including "sixteenths, thistlesticks, justice," uttered in the frame "The word I said was......"

Although the artificial palate was worn throughout the experiment, permanent recordings of tongue-palate contacts were made only of the first two sentences mentioned above, though sound recordings were made of all the utterances.

2.2. Instrumental Methods and Measurements Taken During the Pilot Experiment

The experimental speech data were recorded on a Revox A77 two-channel tape-recorder (frequency response, 2 - 3db : 30 c/s - 20 kc/s) using EMI 88/12 tape at $7\frac{1}{2}$ ips., in an acoustically dampened recording studio. The microphone used was a Sennheisser studio microphone, type MO 211 which was situated 9 inches from the subject's mouth. The electropalatograph used for providing a permanent record of tongue palate contacts was the Prototype 1 machine with the 40-contact artificial palate described in Chapter 4. A mechanically-driven cine-camera (Paillard Bolex, using Kodak Tri-X reversal film, 200 ASA) with a speed of 64 frames per second was used for the purpose of providing a permanent record of tongue palate contacts as shown on the display screen.

Spectrograms were made from the tape recordings of all the test passages spoken under both experimental conditions and the following measurements were taken from these spectrograms:

(1) Lowest limits of the main frequency spectra for all occurrences of [s] and [ʃ].

(2) Duration of the complex contoids in the utterance including [s], [ʃ], [dʒ], [tʃ], [t r].

(1) The lowest limit of the main frequency spectrum was obtained from a broad-band, (0 - 8,000 c.p.s. range) spectrogram using a Sound Spectrograph (Kay Sonagraph, type 7029A). Where it was difficult to measure the point of lowest frequency, a number of amplitude sections (usually about three) were taken from various parts of the articulation. Each recording was followed by a calibration tone consisting of a "pip" from a square wave of 500 c.p.s. from a signal generator. This was used as a scale by which to measure the lowest frequency limit for each of the fricatives.

Of all the possible acoustic features characterizing the fricatives, the value of the lowest limit seemed to be the best and most convenient measure. Other possible measurements such as extent of frequency range (by measuring the upper and lower limits of each fricative frequency spectrum) and frequency of the main formants were mostly found to change proportionately to the lowest frequency level. Thus when the lowest level was raised, the whole frequency range was raised, making not only the upper limit, but also the formant frequencies of the fricative higher as well.

(2) The duration of each of the complex contoids was measured directly from the spectrograms after segmentation procedures had been carried out. For the complex articulations [dʒ], [tʃ], [t r] the whole duration i.e. including both the hold and release phases was measured.

In the analysis of the electropalatograph film, a number of difficulties became evident. Firstly, no adequate synchronization scheme was used so it was difficult to relate directly the acoustic signal from the spectrograph with articulatory data from the electropalatograph film. One of the main difficulties in attempting to synchronize the two sets of data was the variation in the speed of the mechanically-driven camera. The speed varied in a non-linear fashion from 40 to 60 frames a second making accurate frame-by-frame correlations with the spectrographic data extremely difficult. However, it was usually possible to segment the utterances fairly accurately on the basis of patterns of tongue contact only, and observations were made of the narrowness of the central groove for [s] and [ʃ] and the timing and articulatory details of the approach and release phases of [s], [ʃ], [tʃ], [t r] in different environments.

No attempt was made to quantify all the articulatory data from the electropalatograph film; close observation of the film, however, led to a number of general conclusions which will be discussed in the results.

2.3. Main Results of the Pilot Experiment

2.3.1. Frequency of Fricatives

Measurements from the spectrograms of all occurrences of [s] and [ʃ] in different environments included in the experimental material, showed that the lowest limit of the fricative frequency of [s] was consistently higher in the nerve block condition, while the frequency of [ʃ] remained approximately similar or sometimes a little higher. Table 1 shows the readings in c.p.s. for each fricative in different environments in both experimental conditions, normal and with lingual block. It appeared also from measurements that the fricative frequencies were slightly more variable under the lingual block condition than in the normal condition.

2.3.2. Duration of Complex Fricatives

Measurements from the spectrograms showed that the duration of complex fricatives was always longer under the lingual block condition (see Table 1).

Sound	Context		Frequency (in k/c) Normal	Frequency (in k/c) Lingual Bl.	Duration (in centisec.) Normal	Duration (in centisec.) Lingual Bl.
[s]	sea	(1)	3.2	3.55	13	18
		(2)	3.05	3.4	13	16
		(3)	3.25	3.35	14	17
		(4)	3.20	3.65	15	18
	sieve		3.20	3.40	11	13
	sifted		3.30	3.70	10	15
	six		3.15	3.55	11	14
	sixteenths		3.20	3.60	11	13
	Smith		3.15	3.40	10	12
	sticks		3.05	3.20	9	11
	justice		3.00	3.45	12	16
	first		3.10	3.55	10	13
	thistles		3.20	3.60	13	17
	miss		3.30	3.55	14	18
[ʃ]	she	(1)	2.05	2.00	12	19
		(2)	2.20	2.25	10	11
	shell	(1)	2.25	2.05	12	18
		(2)	1.90	2.05	15	24
		(3)	1.85	2.00	11	19
	sure		1.80	1.95	17	20
	fish		2.20	1.95	18	20
[dʒ]	German		-	-	15	18
[tʃ]	church		-	-	16	20
	church		-	-	15	16
[tr]	tree		-	-	15	18

Table I. Lowest limit of frequency spectra and duration measurements for some complex articulations in a number of different environments under normal and lingual block conditions.

2.3.3. Place of Articulation

Close observation of the electropalatograph film indicated generally a larger area of contact made by the tongue on the palate during the lingual block condition than during the normal condition. This was particularly noticeable in the case of the complex fricatives [s] and [ʃ] where the central groove was generally narrowed under the lingual block condition (see Chapter 5 for a discussion of central grooving as one of the articulatory exponents of "complexity"). The narrowness of the groove suggests that the tongue margins were forced up towards the sides of the palate, probably by the increased contraction exerted by the posterior genioglossus, the styloglossus and the transversus muscles. The resulting closer constriction (assuming factors such as airflow to be constant) probably accounts for the higher frequency level of these fricatives during the nerve block condition.

No quantitative measurements were made from the electropalatographic film in the pilot experiment as this was meant only to provide a rough assessment of the type of results one could expect in a more carefully controlled experiment.

2.4. Interpretation of Results in the Pilot Experiment

One of the most interesting results of the pilot experiment was the observed "overshooting" of the target position for fricative articulations under the lingual block anaesthesia condition. In attempting to explain this phenomenon, the notion of "pre-tuned" schemas (see above Chapter 2, section 1.3.3.) should be kept in mind. In discussing this notion we saw how, for any given articulation, the C.N.S. probably "primes in advance" a plan specifying not only the motor commands to the appropriate muscles but also a pattern of afferent signals from sensory receptors likely to be involved in the successful performance of the target articulation. Now, under conditions of bilateral lingual block, some of these receptors, particularly in the front part of the tongue, will be inhibited. If this occurs during the execution of the planned articulation, the anticipated sensory information will not be received according to the expected afferent plan and this may set off a reflex mechanism, bringing the tongue closerto the palate in an attempt to bring into operation more receptors, to achieve a better approximation to the planned amount of sensory information. (The concepts of "amount" of sensory information will be discussed at greater length in the conclusion of the main experiment reported below). As the tongue is forced closer to the palate, the groove will be narrowed, resulting in the "overshooting" effect observed on the electropalatograph in the pilot experiment. Also, as seen earlier, this narrowed groove probably accounts for the higher frequency level of the fricatives during the lingual block condition.

Although the pilot experiment was very limited in scope, involving as it did only two experimental conditions(the normal and lingual block condition) the results can nevertheless form the basis for suggesting a number of interesting hypotheses which could be tested in a full-scale experiment. There are two main hypotheses and a number of subsidiary hypotheses suggested by the pilot experiment. The two main hypotheses are:

1. During speech production, afferent information is used to control ongoing motor performance. Thus any alteration in the feedback of this afferent information will have some (measurable) effects on speech performance.

2. Different types of sensory resources (tactile, proprioceptive or auditory) contributing to the feedback of afferent information may play different roles in controlling speech performance.

Arisingfrom 2 are a number of subsidiary hypotheses:

(i) Tactile sensory resources play an important role in the myodynamic control of those articulations involving relatively large areas of tongue contact with the palate (e. g. most consonants and some close vowels).

(ii) Auditory sensory resources are more important in the myodynamic control of those articulations involving relatively smaller areas of tongue contact with the palate (e. g. most vowels).

(iii) Proprioceptive sensory resources are important in the control of those articulations requiring specific positioning of the tongue, whether or not contact is made with the palate.

These hypotheses will be tested in a full scale experiment involving controlled interference with the stated different types of feedback resources and investigation of the effects such interference has on speech performance. An explanation for these effects will be sought in the "priming in advance" notion mentioned above.

3. DESCRIPTION OF THE MAIN EXPERIMENT

3.1. General Outline of the Experiment

The basic design of the main experiment was similar to that used in the pilot experiment. However, there were a number of important modifications; a large number of experimental conditions, including now not only lingual block conditions, but topical anaesthetic and auditory masking were used; the subject repeated test material a number of times under each experimental condition rather than just once, to allow inter-repetition variability to be assessed; the entire experiment was performed on two separate occasions (two days apart), to assess variability of the effect of the anaesthetic and masking techniques; a testing procedure was used to assess the degree of decrement of sensory sensitivity under each experimental condition; and measurements were made of a wider range of acoustic and articulatory features than in the pilot experiment.

As mentioned earlier, the main aim of the experiment was to investigate the effect of altering different sensory feedback channels on various acoustic and articulatory aspects of speech production.

3.2. Experimental Design

3.2.1. Experimental Conditions

The test data consisted of a short sentence repeated a number of times under eight experimental conditions:

(1) Normal (N)

(2) Topical anaesthetic applied to the surface of the tongue (T)

(3) Binaural high-amplitude auditory masking (A)

(4) Combination of topical anaesthetic and auditory masking (T-A)

(5) Unilateral lingual block anaesthesia (L)

(6) Combination of lingual block and topical anaesthetic. (L - T)

(7) Combination of lingual block and auditory masking (L-A)

(8) Combination of lingual block, topical anaesthetic and auditory masking (L-T-A)

As in the pilot experiment, the normal condition involved no alteration in any feedback channel. As explained earlier, the artificial palate was worn at all times throughout the experimental procedure, including the normal condition.

The anaesthetic techniques require careful control so each technique will be described in detail.

3.2.1.1. Lingual Block Procedure

In the main experiment, unilateral lingual block was used instead of bilateral lingual block, following medical advice that bilateral lingual block conditions were likely to cause severe traumatic ulcers (Sprinz, 1970), and were to be avoided if possible. The anaesthetic injection was therefore given on the left side only, using the following procedures:- The needle used was 42 mm. long with an 0.45 mm. bore. It was inserted at the pterygo-mandibular fold about 2 cm. above the occlusal plane of the mandibular teeth. The direct method of insertion was used, which involved piercing the mucuous membrane, the superior constrictor muscle, fat and the interior pterygoideus muscle until contact with bone (i.e. the ramus of the mandible above the mandibular foramen) was established. (see above Fig. 29 for place of insertion of the needle) The needle was withdrawn slightly and a prescribed amount of anaesthetic solution was injected at the mandibular foramen. For this experiment 1.7 ml. of 2% xylocaine (with Noradrenaline) was used as the anaesthetic. To ascertain that the anaesthetic was having effect, the dental anatomist asked the subject to determine whether there was any altered sensation in the lower lip. If the anaesthetic was having effect in blocking the lingual and inferior alveolar nerves, a tingling is usually felt on the lower lip.

Maximum effect was felt approximately eight minutes after injection and lasted for 55 minutes.

Although one cannot guarantee that the effect of anaesthetic on the lingual nerve would be exactly the same on two separate occasions, precautions were taken to ensure that all possible factors were kept as constant as possible; the two injections took place in the morning at the same time of day, and were given by the same dental anatomist, and on each occasion the subject had previously eaten a large meal to prevent possible side effects from the adrenaline in the anaesthetic solution. As far as one could ascertain, the subject was in the same physiological state on both occasions the experiment took place.

After each administration of the anaesthetic, a test was carried out to ascertain whether the extent of diffusion of the drug was similar on both occasions. This test consisted of drawing a line on the subject's face, from his bottom lip to his chin, marking the boundary of sensitivity. As the drug was administered unilaterally (on the left side), the line was expected to bisect the lip and chin. A photograph was taken of the subject's face with the line drawn in, 40 minutes after each administration of the drug. The positions of the lines, indicating the extent of diffusion, could then be compared.

It was hypothesized that the lingual block as administered above affected the organized sensory endings and free endings in the lamina propria in the left anterior two-thirds of the tongue. The periodontal receptors also would be affected as they are supplied by the inferior alveolar nerve (see Chapter 2, section 1.3.2.). It is possible also that the muscle spindles in the anterior part of the tongue also were affected (see above section 2.).

Although one cannot be too dogmatic about the diffusion effects of any drug such as xylocaine throughout the oral region, one can fairly confidently assert that the anaesthetic had no effects on the motoneurones in the tongue. There is a slight possibility, however, that lingual block procedures may affect some of the motoneurones supplied by the inferior alveolar nerve i.e. those associated with the mylohyoideus and anterior belly of the digastricus muscles. (see Fig. 29, section 1.2. above).

3.2.1.2. Topical Anaesthesia

The topical anaesthetic used was 10% xylocaine solution applied from an aerosal pack by means of a metered valve, allowing 10 mg. per spray application. It was applied as follows: Four sprays were first applied to the tongue surface (application 40 mg.), then swabbed with cotton buds. After two minutes, four more sprays were applied (total application 80 mg.). The maximum effect of the anaesthetic seemed to begin about five minutes later and continued for a further 10 minutes. There were no carry-over effects, the drug being totally absorbed after 20 minutes. The subject was instructed to exhale during application of the anaesthetic to prevent HCI fumes reaching his lungs. The amount used for this experiment was well within the recommended safety limits of 200 mg. per single application.

The extent of penetration of topical anaesthetic as we saw above is not known with any certainty. It is probable that it does not penetrate to the deeper layers of the lamina propria and almost certainly would not affect the muscle spindles in the tongue. One could plausibly assume, therefore, from a knowledge of the structure of the tongue dorsum, that topical anaesthetic would affect most of the superficial free endings in the epithelium and in the connective tissue between papillae.

3.2.1.3. Binaural Auditory Masking

Auditory masking was provided by 100 db. white noise (narrow band, central frequency 1 K/c.p.s.) from a Peters Audimeter (Model AP 5). This level was decided after a series of trials when the db. level and frequency were altered in steps to find the optimum masking level which would eliminate all auditory feedback through the air and at the same time not cause any undue discomfort to the subject.

3.3. Experimental Procedure

The subject was the same as the one who participated in the pilot experiment. He was a native speaker of Educated Australian English.

The lingual block was administered by a skilled dental surgeon using the procedure outlined in the previous section. Approximately eight minutes after injection of the anaesthetic the subject was seated in an acoustically damped recording studio wearing the electropalatograph,(using Palate No. 2 in Fig. 19, Chapter 4). The four experimental conditions involving lingual block (i. e. conditions 5, 6, 7, 8 above, section 3. 2. 1.), were randomly administered with a break of about 10 minutes between each condition. The other four experimental conditions, i. e. those not involving lingual block, were administered in the afternoon of the same day. During each experimental condition, the subject repeated six times the passage : "Did <u>she</u> see what <u>Shaw</u> saw" (with tonics on <u>she</u> and <u>Shaw</u> (see Halliday, 1967)), using the same intonation pattern and trying to maintain standard tempo, and pitch-and loudness-ranges.

The whole experiment was repeated two days later making a total of 12 repetitions of the passage under each experimental condition. The main reason for repeating the experiment was to determine whether lingual block could have a different effect on two separate occasions.

During the experiment, the electropalatograph display screen, illuminated by arc-lights, was situated beside the subject on a table facing a window in the experimental room. An electrically-driven cine-camera (Telford 16 mm., type N. 136 using Kodak Tri-X reversal film : 200 ASA), running at 100 frames per second, photographed the contact patterns on the display screen from a darkened room on the other side of the window. (see Photograph no.4 inside back cover).

The test passages were recorded onto one track of a two-channel Revox tape-recorder. (The recorder, tape and microphone were the same as those used in the pilot experiment (see above section 2. 2.)). The other track of the recorder contained a 4 c. p. s. click from a Kay Sonagraph 6077A time-mark generator, synchronized both with the starting switch of the camera and a timing read-out panel situated on the left of the electropalatograph display screen (see Chapter 4, section 2. 2. 4. 2). This synchronization facility was not available in the pilot experiment, and enabled one to accurately correlate the articulatory pattern from the contact screen at any particular time with the acoustic pattern from the sound spectrograph.

Originally, it was intended to carry out the testing procedure for sensory decrement (see section 1. 3. above) immediately prior to recording the test passages under each experimental condition. It was soon found however, that, because of the temporal limitations imposed by the anaesthetics (see sections 3. 2. 1. 1. and 3. 2. 1. 2. above) the testing procedure could not effectively be conducted during the experiment. The testing was therefore carried out under the same eight experimental conditions at a later date, a few weeks after the actual experiment. It was hypothesized that the effect on tactile sensitivity of the anaesthetic and masking procedures would be the same on this later occasion as during the experiment. A detailed description of the instrumentation and the method of determining the oral tactile threshold for each experimental condition is included later in section 3. 5.

As in the pilot experiment, acoustic and articulatory measurements were made of the test passages using various experimental techniques including sound spectrography and electropalatography. An attempt was made in the main experiment to quantify the electropalatographic data in some way rather than to rely on subjective impressions gained from close observation of the EPG display screen as was the case in the pilot experiment. The techniques of measuring the acoustic and articulatory data will be discussed in some detail.

3. 3. 1. Measurements from the Sound Spectrograph.

As in the pilot experiment, spectrograms were made from the tape-recordings of all the test passages spoken under all experimental conditions. A minimum number of three spectrograms were made for each of the passages. These included :

(a) a broad-band spectrogram, speed 5. 14" sec., scale 0-8, 000 c. p. s.

(b) a broad-band spectrogram, speed 5. 14" sec., scale 0-4, 000 c. p. s.

(c) a narrow-band spectrogram, speed 5. 14" sec., scale 0-2, 000 c. p. s.

The following measurements were taken from the spectrogram:

(1) The Lower and higher limits of the main frequency spectra for the four test fricatives [s] in "see", [s] in "saw", [ʃ] in "she" and [ʃ] in "Shaw", (written henceforth as "s̲ee", "s̲aw", "s̲he", "S̲haw", respectively).

(2) The duration of all vocoids and contoids in the test passages.

(3) The fundamental frequency of voiced segments in the test material.

(4) The centre frequency of the first and second formants for each vocoid in the test passages.

In addition to these measurements, some informal auditory judgments were made by trained phoneticians on features such as the loudness and phonetic quality of articulations under the different experimental conditions.

3.3.1.1. Frequency Spectra of the Fricatives.

The lower and higher limits of the main part of the frequency spectrum for each of the four fricatives were judged by eye from the broad-band spectrograms (scale 0-8,000 c.p.s.). As in the pilot experiment, where it was difficult to measure the point of lowest frequency, a number of amplitude sections were taken from various parts of the fricative (see section 2.2.). In general, however, these amplitude sections were found to vary so greatly even when taken close together, that they were of limited use only. In most cases, the lower limit of the main part of the spectrum could be delineated by eye reasonably accurately.

The upper limit of the spectrum was, however, a little more difficult to measure accurately by eye. Frequently, the gain had to be boosted in the upper frequency range before any frication was visible at all. Where the frequency went beyond 8,000 c.p.s., a broad-band spectrogram with the extended range 0-16,000 c.p.s. was made. Even with the extended scale, however, it was frequently difficult to discern any clear cut-off point in the frication. Rather it tended, especially for [s], to fade out gradually. For this reason, some of the measurements of upper frequency level were somewhat arbitrary.

3.3.1.2. Duration of Segments.

The duration of segments in the test passages were measured from the broad-band spectrograms. Accurate measurements to the nearest millisecond were made of the following sounds:- [ɩ] in "did", [ʃ] and [i] in "she", [s] and [i] in "see", [ʃ] and [ɔ] in "Shaw", [s] and [ɔ] in "saw". In addition, the total duration of each sentence, from the beginning of the closure for the initial [d] to the end of the formant registration for the final [ɔ] in "saw", was noted for each repetition. For the purposes of measurement, the duration of each of the four fricatives was taken to be that portion on the spectrogram showing clearly a band of fricative noise.

3.3.1.3. Fundamental Frequency.

The fundamental frequency was measured from narrow-band spectrograms, scale 0-2,000 c.p.s. A curve representing the change in fundamental frequency was traced from the fifth harmonic, which was always clearly visible on the spectrogram. This curve was made for each of the voiced segments in all the test passages under the eight experimental conditions.

Although it was clear from listening to the tapes of the test passages that the fundamental was higher than the normal under some experimental conditions, it proved a difficult task to quantify these differences adequately. One of the problems was the relatively great variability both of segment duration and of fundamental frequency under different experimental conditions, particularly the L-A and L-T-A conditions. After experimenting with different types of graphic representation, it was decided that the most useful way of comparing the fundamental frequency under different experimental conditions was to superimpose all the fundamental frequency curves for a given voiced segment or series of segments under a given experimental condition, and to draw by hand what seemed to be the average fundamental frequency. The fundamental frequency curves so drawn are presented later (see section 3.4.1.3.).

3.3.1.4. Formant Frequencies of Vocoids

It was hypothesized that the phonetic qualities of some vocoids in the test passage would change under some experimental conditions, particularly those involving auditory masking, and that this change in phonetic quality could be characterized in part by a change in the frequencies of the first and second formants of these vocoids. It must be emphasized, however, that specification of phonetic quality wholly in terms of formant frequency levels is frequently unreliable (see Ladefoged, 1967a).

The centre frequencies of the first two formants of the following vocoids in the test passage were measured:

(a) [ɩ] in "did".

(b) [i] in "she" (written henceforth as "sh<u>e</u>")

(c) [i] in "see" (written "s<u>ee</u>")

(d) [ɔ] in "Shaw" (written "Sh<u>aw</u>")

(e) [ɔ] in "saw" (written "s<u>aw</u>")

The formant frequencies were measured from the broad-band spectrograms (scale 0-4, 00 c. p. s.) to the nearest 5 c. p. s. Where it was difficult to separate the first and second formants e. g. as in the back vowel [ɔ], a number of amplitude sections through the level part of the formant were taken.

3.3.2. Measurements from the Electropalatograph

The films taken of the display screen of the electropalatograph as the subject read the test passages were viewed carefully frame-by-frame through a film editing machine, (Premier "Editor", manufactured by Robert Rigby). This machine could be manually controlled so that any single frame could be held static in a viewing screen and the pattern of contacts transcribed at leisure.

As the detailed manual analysis of high-speed film is extremely laborious and time-consuming, it was thought sufficient for the purpose of this experiment to analyse the relevant parts of the films taken on the second replication of the experiment only. The hypothesis underlying this selection, i. e. that the results of the first and second replication would be similar, seems justified on the basis of the acoustic data obtained (see section 3.4. below).

The patterns of tongue contacts during the articulation of the four fricatives "see", "saw", "she" and "Shaw" in each of the eight experimental conditions were transcribed frame-by-frame from the editing machine's screen onto specially marked sheets, (for the format of these marked sheets see later Fig. 33, section 3.4.2.1.). A record of the frame number was kept by referring to an accurate frame counter on the Editor. Using the synchronization system outlined above (section 3.3.), it was possible to correlate accurately a particular frame with any point on the spectrogram. The place chosen as the starting point of each fricative was the first appearance of frication on the spectrogram. The frame number at this point was called frame no. 1 and consecutive frames were transcribed until the end of the fricative pattern on the spectrogram. The number of frames representing the duration of the fricatives varied, of course, between different experimental conditions.

The following measurements were taken from these basic transcriptions of the contact patterns for the four fricatives:

(1) Maximum area of the palate touched by the tongue at any one time (i.e. in any single frame) during the production of each fricative (expressed in terms of touched contact points on the artificial palate).

(2) The changing width of the narrowest part of the central groove in the alveolar region for each fricative (expressed in terms of the number of untouched contacts in the "alveolar zone"). (see later Figs. 30, and 34-40).

(3) The changing width of the narrowest part of the central groove in the palatal region for each fricative (expressed in terms of the number of untouched contact points in the "palatal zone"). (see Fig. 38, below).

(4) Asymmetrical movements of the tongue during articulation of the fricatives.

(5) Most forward contact of the tongue on the palate during the articulation of each of the fricatives under the different experimental conditions.

As the methods of measuring some of these five variables were relatively complex, they will be discussed at some length.

3.3.2.1. Maximum Area of Contact

As mentioned above (section 2.4.) one of the basic hypotheses to be tested in this experiment is that different sorts of sensory feedback have important roles to play in the control of articulations such as [s] and [ʃ] involving contact between the tongue and palate. It seemed plausible from the results of the pilot experiment that, under experimental conditions of sensory interference, particularly those involving lingual block, the contact patterns for the four test fricatives "see", "saw", "she", "Shaw" would be altered in some way. The altered pattern of contact may be manifested by differences in overall contact area arising probably from the effect of narrowing of the central groove noted in the pilot experiment. One would expect that under conditions of sensory feedback interference, the overall area of contact would increase, reaching a maximum in the L-T-A condition.

A simple measurement was devised to determine whether the area of contact for the fricatives was different under the eight experimental conditions. The contact patterns for each repetition of the fricatives were carefully analysed frame-by-frame, and the maximum number of contact points which were touched at any one time (i.e. in any one frame) was noted. In attempting to quantify the area of contact in this way, one makes the assumption that the contact points are a similar distance apart from each other. This is not always the case, so the implications of such a test should be regarded with caution. However, it does give some indication of differences under each experimental condition.

3.3.2.2. Narrowness of Central Groove in the Alveolar Region.

In Chapter 5, the tongue configurations for the complex fricatives [s] and [ʃ] were discussed. It was hypothesized that in this subject's articulation of [s] and [ʃ], a central groove in the tongue was always present. (For the purposes of this investigation, "central groove" is defined as "the narrowest space on the palate left untouched by the tongue during fricative production").

There were, however, differences in the area of contact made by the tongue on the palate for these two articulations. The palatograms in Fig. 20 for instance, show that the lateral contact of the tongue is further forward for [s] than for [ʃ] in similar environments (e.g. before [i] and [ɔ],) although the central groove appears narrower in [ʃ].

The pilot experiment described in section 2 showed that under the lingual block condition, one of the "overshooting" effects illustrated by EPG was the narrowing of this central groove in both [s] and [ʃ], although no quantitative measurements were taken. It seemed plausible that this narrowing effect would also occur under other conditions of sensory deprivation, including unilateral, rather than bilateral lingual block, and auditory masking. An attempt was made therefore to quantify the difference in the width of the groove under the different experimental conditions. For this purpose, the EPG display screen was divided up into a number of vertical and horizontal "zones" such that any contact point could be specified in terms of these zones. Fig. 30 shows the screen divided up into numbered zones. For measurement of the width of the central groove, the horizontal zone no. 3 (the "alveolar plane" zone) was chosen, as this was the region in which most difference was evident in the pilot experiment. The width of the groove was expressed in terms of untouched contact points in this one horizontal plane. Graphs were drawn with the number of untouched contact points plotted against time expressed in numbers of film frames per second. (see Figs. 34, 35, 36, 37 later in section 3.4.2.2.). Using this scoring system, maximum width of the groove would have all seven contacts left untouched (=7 on vertical axis) and minimum width would have only one contact e.g. the middle one, untouched (=1 on the vertical axis). In this way it was possible to plot the change in groove-width against real-time.

As there was some variability in the contact patterns between repetitions under each experimental condition, a mean "groove-width graph" for each of the four test fricatives under each experimental condition was obtained. This was done by obtaining the average width of the groove expressed in terms of untouched contacts (in zone 3

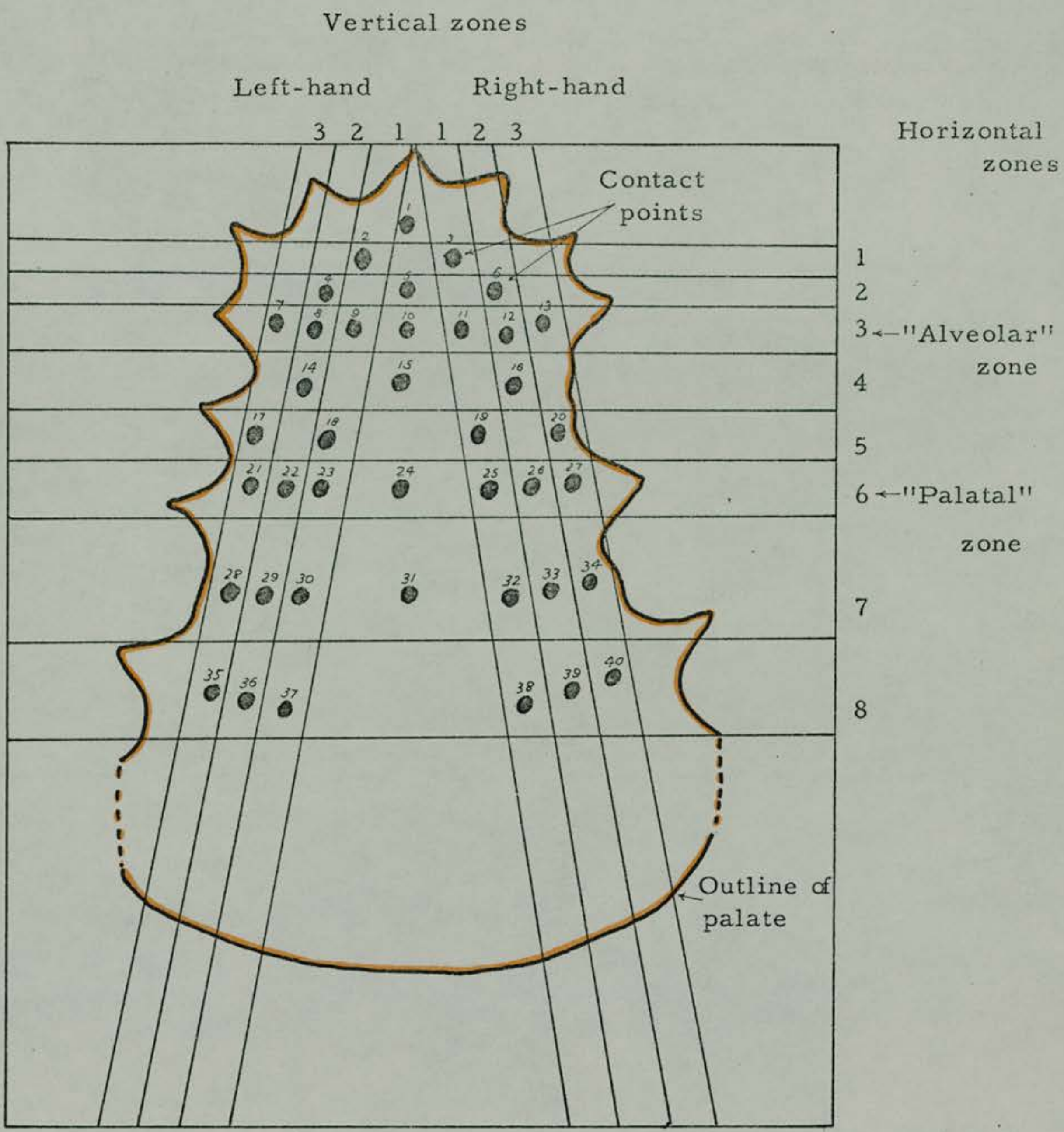


Fig. 30. Diagram of the electropalatograph display screen showing the horizontal and vertical reference zones used for specifying the position of the contact points. The graphs illustrated later in Figs. 34-39 were drawn with reference to this zoning scheme.

mentioned above) every two frames for each of the six repetitions of the fricatives. These average measurements were plotted on a graph and the points joined forming the mean groove-width curve, for each of the four fricatives under the eight experimental conditions.

3.3.2.3. Narrowness of the Central Groove in the Palatal Region

The measurements described in the previous section were for the narrowness of the central groove in the alveolar region only. It was hypothesized, however, that the central groove in the post-alveolar region would vary also under different experimental conditions. The width of the groove in the palatal region was measured at horizontal zone 6 (see Fig. 30 for reference zones) in the same way as described in the previous section for the measurements in the alveolar plane.

3.3.2.4. Asymmetrical Movements of the Tongue.

As mentioned earlier in the discussion on instrumental techniques used in studying lingual articulation (Chapter 3, section 1.1.1.), the configuration of the tongue is frequently asymmetrical during speech. Observation of the EPG data in this experiment clearly shows that this asymmetry occurs in this subject's articulation of [s] and [ʃ]. The asymmetrical movements of the tongue can be illustrated schematically using the zoning system of the palate shown in Fig. 30. Separate graphs were plotted for the contacts made by the left and right sides of the tongue. The number of the vertical zone within which a contact point was touched represented the vertical axis of the graph (see later Figs. 39, 40); e.g. if contact number 8 (see Fig. 30) was touched, this would be represented on the graph as 2 (for vertical zone no. 2). Separate curves plotting the change in contact patterns against time (expressed in film frames per second) were drawn for the left and right sides of the tongue during each repetition of the fricatives in the eight experimental conditions.

3.3.2.5. Forward Contact of the Tongue.

It was mentioned in section 3.3.2.1. that one of the manifestations of increased overall contact area during the production of [s] and [ʃ] may be the narrowing of the central grooves. Methods of quantifying in some way the change in width of the central groove were discussed in sections 3. 3. 2. 2. and 3. 3. 2. 3. Another manifestation of the increased contact area may, however, be the fronting of tongue articulation causing a more forward contact with the palate, (e. g. in horizontal zones 1 and 2) in addition to narrowing the groove. Initial observation of the EPG film indicated that in fact in some experimental conditions, the tongue moved further forward on the palate than in the normal condition. The position of contact for each fricative was therefore scrutinized with reference to the zoning scheme outlined in section 3. 3. 2. 2. and Fig. 30, and those articulations involving contacts in horizontal zones 1 and 2 were noted.

3.4. Discussion of Results of Main Experiment.

3.4.1. Results of Measurements Taken from the Sound Spectrograph.

Measurements of the fundamental frequency, segment duration, formant frequency levels and frequency spectra of fricatives were made using the techniques described in section 3. 3. 1. For each of these speech output variables, an IBM 360/50 computer was programmed[1] to produce the following:

(a) means for the total 12 observations (6 on each replication of the experiment) under each of the eight experimental conditions.

(b) the average of condition variances for the 12 observations.

(c) standard error of means in (a).

(d) two-way tables of means for all experimental conditions.

(The computer print-outs for each speech variable are included in Appendix I.).

The condition variance was calculated for each replication of the experiment from the formula :

$$\sum_{i=1}^{6} \frac{(x_i - \bar{x})^2}{5} \quad \text{(where } \sum = \text{sum, } \bar{x} = \text{mean)}$$

The average condition variance was obtained by halving the sum of the variance figures for each replication. The variances were compared using a standard "F" test (significant at the 5% level).

1. The programme was written by Miss L. Marrett of the Statistics Department, University of Edinburgh.

The standard error of condition means was obtained from the formula :

$$\text{S. E.} \quad \sqrt{\frac{\text{average variance}}{12}}$$

The presentation of some of the data in terms of two-way tables may require some explanation. In statistical terms, this experiment is designed as a factorial experiment in which three factors (i. e. lingual block, topical anaesthetic and auditory masking) each at two levels (presence and absence) are used in all possible combinations, resulting in a total of eight experimental conditions. The particular advantage of such an experiment is that it is possible to obtain a good estimate of the main effect that any one factor has on a particular speech variable by comparing all those conditions involving that factor with all those conditions not involving it. Such information can be presented by means of two-way tables which give a better estimate of the main effects of particular factors than, for instance, if one compared simply one condition at a time with the normal condition. Thus the main effect of, for instance, condition L on a particular speech variable would be regarded as the difference in effect between the mean of those four conditions involving L (i. e. L, L-T, L-A, L-T-A) and the mean of the other four not involving L (i. e. N, A, T, T-A). Two-way tables will also show interactions between different conditions i. e. whether a particular condition behaves differently in the presence of another.

All the speech variables measured showed such different variances under different experimental conditions, that standard analysis of variance procedures were not possible. The high variance of some measurements seemed due to the effects of sensory feedback alteration rather than to normal experimental error. This was not entirely unexpected as it seemed plausible that one would generally experience more difficulty in achieving different articulatory targets consistently when deprived of normal sensory feedback.

Tables 2 and 3 show the means, variances and standard errors for the following speech output variables: lower limits of frequency spectra of the four test fricatives "see", "saw", "she", "Shaw"; first and second formant levels for the four vocoids "she", "see", "Shaw", "saw" (Table 2); duration of segments "she", "she", "see", "see", "Shaw", "Shaw", "saw", "saw", [ɪ] in "did" and

Speech Output Variables (in c.p.s.)			N	T	A	T-A	L	L-T	L-A	L-T-A	Mean
Fricative freq.	"see"	Mean	3,171	3,183	3,150	3,329	3,354	3,379	3,450	3,454	3,454
		Var.	17.10	78.32*	114.20*	72.12*	47.08	52.14*	71.69*	147.07*	
		S.E.	11.93	25.54	30.85	24.51	19.80	20.84	24.44	35.00	
	"saw"	Mean	3,046	3,292	3,221	3,462	3,254	3,404	3,350	3,558	3,323
		Var.	72.11	194.22	477.07*	215.45*	110.43	60.46	74.17	361.66*	
		S.E.	24.51	40.23	63.05	42.37	30.33	22.44	24.86	54.89	
	"she"	Mean	2,279	2,271	2,254	2,308	2,346	2,287	2,275	2,192	2,278
		Var.	40.41	45.40	75.40	133.32*	57.08	73.74	111.66	115.82	
		S.E.	18.35	19.45	25.06	33.33	21.81	24.79	30.50	31.06	
	"Shaw"	Mean	2,283	2,229	2,196	2,337	2,229	2,192	2,279	2,321	2,258
		Var.	93.32	177.07	25.40	93.74	161.09	35.82	60.41	72.08	
		S.E.	27.88	38.41	14.55	27.95	36.75	17.27	22.43	24.50	
Formant freq.	"she" F1	Mean	413	420	412	427	412	381	400	367	404
		Var.	4.73	6.12	2.92	8.81	5.61	4.90	1.45	8.23	
		S.E.	6.28	7.14	4.93	8.57	6.84	6.39	3.47	8.28	
	"she" F2	Mean	2,018	2,000	1,961	1,927	2,015	1,999	1,955	1,910	1,973
		Var.	8.84	6.73	14.92	16.83	9.68	9.93	207.39*	22.78	
		S.E.	8.58	7.49	11.15	11.84	8.98	9.09	41.57	13.77	
	"see" F1	Mean	407	408	430	425	397	393	397	391	406
		Var.	3.95	2.40	7.52	4.85	5.89	1.02	4.89	11.43*	
		S.E.	5.74	4.48	7.91	6.35	7.00	2.91	6.38	9.76	
	"see" F2	Mean	1,985	1,951	1,898	1,875	2,002	1,975	1,917	1,890	1,937
		Var.	8.67	4.86	15.76	10.89	10.25	15.45	17.34	26.25*	
		S.E.	8.50	6.36	11.46	9.50	9.24	11.34	12.02	14.79	
	"Shaw" F1	Mean	475	474	485	478	459	449	460	459	467
		Var.	7.29	4.68	1.42	3.30	.90	7.85	9.31	3.74	
		S.E.	7.79	6.24	3.44	5.24	2.74	8.09	8.81	5.58	
	"Shaw" F2	Mean	826	825	867	877	810	800	843	816	833
		Var.	2.48	8.79*	7.36*	8.80*	5.69	5.41	4.74	6.45	
		S.E.	4.55	8.56	7.83	8.56	6.88	6.71	6.28	7.33	
	"saw" F1	Mean	472	473	509	479	462	453	499	500	481
		Var.	3.08	2.13	2.60	10.85*	1.50	1.64	8.70	2.82	
		S.E.	5.07	4.21	4.66	9.51	3.53	3.69	8.51	4.84	
	"saw" F2	Mean	809	808	840	821	789	786	832	818	813
		Var.	2.13	1.08	2.11	3.35	2.15	5.60	5.81	3.53	
		S.E.	4.21	3.00	4.20	5.29	4.24	6.83	6.96	5.42	

Table 2. The average means, variances, and standard errors for two speech variables: lower limit of fricative frequency and formant levels of vocoids. For the sake of clarity, the means are taken to the nearest 1 c.p.s. and the variances are expressed as $\frac{1}{100}$th. their real values. Those variances marked with an asterisk are significantly greater than the normal (at the 5% level) (For a complete table of means, variances and S.E.s for both replications, see computer read-out in Appendix 1)

Duration of Segments (in centisec.)		Experimental Conditions								
		N	T	A	T-A	L	L-T	L-A	L-T-A	Mean
[ʃ] "she"	Mean	16.34	16.31	21.74	21.06	18.58	19.92	22.63	23.50	20.01
	Var.	.65	2.00*	3.61*	6.26*	5.06*	7.56*	10.30*	13.19*	
	S.E.	.23	.41	.55	.72	.65	.79	.93	1.05	
[i] "she"	Mean	15.77	18.61	21.16	21.96	17.65	18.70	21.96	21.77	19.70
	Var.	1.37	1.39	5.22*	3.00	2.30	3.01	5.77*	11.04*	
	S.E.	.34	.34	.67	.50	.44	.50	.69	.96	
[s] "see"	Mean	13.88	16.15	16.28	17.08	14.84	16.47	16.41	17.39	16.06
	Var.	.20	1.15*	1.23*	6.23*	1.88*	1.54*	4.57*	2.58*	
	S.E.	.13	.31	.32	.72	.40	.36	.62	.46	
[i] "see"	Mean	8.33	10.53	11.9	12.22	9.32	10.44	11.14	12.16	10.76
	Var.	1.03	1.56	2.45	1.22	.39	1.09	2.97*	2.53	
	S.E.	.29	.36	.45	.32	.18	.30	.50	.46	
[ʃ] "Shaw"	Mean	15.32	16.92	19.31	18.64	16.60	17.27	18.70	21.06	17.98
	Var.	.38	1.16*	5.85*	9.97*	1.19*	2.14*	8.85*	14.49*	
	S.E.	.18	.31	.70	.91	.31	.42	.86	1.09	
[ɔ] "Shaw"	Mean	18.45	19.60	22.82	22.79	18.58	19.76	22.12	23.08	20.90
	Var.	.50	1.02	2.71*	3.42*	.84	2.30*	2.03*	3.90*	
	S.E.	.20	.29	.48	.53	.26	.44	.41	.57	
[s] "saw"	Mean	13.27	15.83	15.41	15.57	13.82	15.67	15.51	17.96	15.38
	Var.	.53	1.75*	.97	5.18*	1.36	2.68*	1.94*	5.85*	
	S.E.	.21	.38	.28	.66	.34	.47	.40	.70	
[ɔ] "saw"	Mean	19.05	18.92	22.44	24.13	20.08	21.26	23.39	24.26	21.69
	Var.	1.29	5.97*	2.92	.85	3.14	3.13	1.38	3.93*	
	S.E.	.33	.70	.49	.27	.51	.51	.33	.57	
[ɪ] "did"	Mean	4.34	5.04	5.62	5.30	6.10	6.42	6.38	8.07	5.91
	Var.	.57	.94	1.71*	.30	.80	1.28	.99	6.88*	
	S.E.	.22	.28	.38	.16	.26	.33	.29	.76	
Total sentence	Mean	166.13	181.32	209.05	214.48	178.35	193.61	209.5	218.69	196.39
	Var.	46	31	169*	97	40	153*	116	133*	
	S.E.	1.95	1.59	3.76	2.84	1.82	3.57	3.11	3.32	

Table 3. The average means, variances and standard errors for the duration of segments. Those variances marked with an asterisk are significantly greater than the normal (at the 5% level).

total duration of the test sentence. (Table 3). The data showed very little difference between the two replications of the experiment, so it was felt appropriate to present the means over a total twelve repetitions.

It can be seen clearly from Tables 2 and 3 that most of the experimental conditions have some effect on the various speech variables. However, it seems from the results that any given condition does not always have the same effect on all the speech variables. For instance, whereas interference with tactile sensation (e.g. under the L-T condition) causes noticeably higher frequency levels for fricatives "see" and "saw", the same conditions cause only very slightly higher levels for "she" and lower levels for "Shaw". As the effects of different experimental conditions on each speech variable are not always the same, the results will be considered in somewhat more detail, making particular reference to two-way tables of means.

3.4.1.1. Frequency Spectra of the Test Fricatives.

For the fricatives "see" and "saw" the effect of all experimental conditions (except A in see) is to raise the normal level of the frequency spectra. For both fricatives, this effect reaches its maximum in the L-T-A condition i.e. that condition with hypothesized greatest sensory deprivation. It is interesting to note from the two-way tables that the effect of auditory masking, lingual and topical anaesthetic seems similar in both occurrences of [s] (compare marginal means of NO-A, A; NO-T, T; NO-L, L for "see" and "saw" in Table 4.)

For fricatives "she" and "Shaw" the tendency is not for the experimental conditions to cause a consistent rise in frequency levels as was the case with [s]. In fact for "she", the average mean for all conditions is almost equal to the N mean, with condition L-T-A causing a lower frequency level, while for "Shaw", the average mean is lower than N with most conditions causing lower frequency levels. These results agree substantially with those obtained in the pilot experiment, although they should be regarded with considerable caution, because of the different variances involved.

Table 2 shows that the condition variances for all experimental conditions except L were significantly greater than the normal for the

Speech Variable	Two-way Tables											
		NO-A	A			NO-T	T			NO-T	T	
Freq. of "see"	NO-L	3,177	3,240	3,208	NO-L	3,106	3,256	3,208	NO-A	3,262	3,281	3,272
	L	3,367	3,452	3,409	L	3,402	3,417	3,409	A	3,300	3,392	3,346
		3,272	3,346	3,309		3,281	3,336	3,309		3,281	3,336	3,309
		NO-A	A			NO-T	T			NO-T	T	
Freq. of "saw"	NO-L	3,169	3,342	3,255	NO-L	3,133	3,377	3,255	NO-A	3,150	3,348	3,249
	L	3,329	3,454	3,392	L	3,302	3,481	3,392	A	3,285	3,510	3,398
		3,249	3,398	3,323		3,218	3,429	3,323		3,218	3,429	3,323
		NO-A	A			NO-T	T			NO-T	T	
Freq. of "she"	NO-L	2,275	2,281	2,278	NO-L	2,267	2,290	2,278	NO-A	2,312	2,279	2,296
	L	2,317	2,233	2,275	L	2,310	2,240	2,275	A	2,265	2,250	2,257
		2,296	2,257	2,277		2,289	2,265	2,277		2,289	2,265	2,277
		NO-A	A			NO-T	T			NO-T	T	
Freq. of "Shaw"	NO-L	2,251	2,267	2,261	NO-L	2,240	2,283	2,261	NO-A	2,256	2,210	2,233
	L	2,210	2,300	2,255	L	2,254	2,256	2,255		2,237	2,329	2,283
		2,233	2,283	2,258		2,247	2,270	2,258		2,247	2,270	2,258

Table 4. Two-way tables of lower frequency means for the fricatives "see, she, saw, Shaw" (in c. p. s.). The marginal means are the outside figures in each table (e. g. marginal means of NO-L, L for "see" are 3,208 and 3,409 respectively).

fricative "see". For "saw", most variances were higher than the normal but only those for conditions A, T-A, and L-T-A were significant. For "she" and "Shaw" however, the variances were not so different from the normal. Only condition T-A for "she" caused a significantly greater variance.

3.4.1.2. Duration of Segments.

As seen in Table 3, all experimental conditions involving sensory feedback alterations caused an increase in duration of most of the segments measured. These results are essentially in agreement with those reported by McCroskey (1958) and Ringel and Steer (1963). Detailed analysis of the results show, however, that certain experimental conditions do not seem to have the same effect on all segments measured. Lingual block and topical anaesthetic conditions seemed to cause little effect on the duration of some vocoids, while they clearly had a considerable effect on some of the fricatives. To illustrate this, two-way tables were compiled from the means in Table 3 of the vocoid [ɔ] in "Shaw" and of the fricative [ʃ] in "she". (see Table 5).

The marginal means in Table 5 show clearly that for [ɔ], sensory tactile feedback alteration by lingual block has almost no effect on the duration (see NO-L, L conditions and NO-L, L under NO-A condition). Conditions involving auditory masking, however, cause a quite appreciable increase in duration (see marginal means for NO-A, A). The situation is somewhat different with the fricative [ʃ]. Here not only auditory masking conditions, but also those conditions involving lingual block and topical anaesthetic, cause a noticeable increase in duration. This applied also to the other three test fricatives. One could tentatively conclude from this that for some articulations (e.g. vocoids involving only small areas of tongue contact with the palate), auditory feedback may play a more important role than tactile feedback in controlling duration. On the other hand, for those articulations involving relatively large areas of tongue-palate contact, (e.g. [ʃ]) not only auditory feedback, but tactile feedback as well, play important roles. It must be emphasized here

Speech Variable	Two-way Tables											
		NO-A	A			NO-T	T			NO-T	T	
Duration of [ɔ] in "Shaw"	NO-L	19.02	22.80	20.91	NO-L	20.63	21.19	20.91	NO-A	18.51	19.67	19.09
	L	19.16	22.59	20.88	L	20.34	21.41	20.88	A	22.46	22.93	22.70
		19.09	22.70	20.89		20.49	21.30	20.89		20.49	21.30	20.89
		NO-A	A			NO-T	T			NO-T	T	
Duration of [ʃ] in "she"	NO-L	16.32	21.40	18.86	NO-L	19.03	18.68	18.86	NO-A	17.45	18.11	17.78
	L	19.24	23.06	21.15	L	20.60	21.71	21.15	A	22.18	22.28	22.23
		17.78	22.23	20.00		19.82	20.19	20.00		19.82	20.19	20.00

Table 5. Two-way tables of duration means of vocoid [ɔ] in "Shaw" and fricative [ʃ] in "she", (in centiseconds). (For a complete set of duration two-way tables for all test fricatives and vocoids see Appendix I).

again, however, that because of the large variances involved, one can only vary tentatively compare means of different variables.

Observation of Table 3 shows that the variances under some experimental conditions are very high. Most conditions involving auditory masking caused significantly higher variances for most segments when compared with the normals. There seemed to be a marked tendency for variances of the complex fricatives [s] and [ʃ] under almost all experimental conditions to be significantly higher than the normal. This tendency was not as evident in the vocoids; in "s<u>ee</u>", for instance, only one condition (L-A) caused a significantly high variance. Some extremely high variances were reported for some of the fricatives (e. g. L-T-A condition for "<u>sh</u>e", T-A and L-T-A conditions for "<u>Sh</u>aw", T-A and L-A conditions for "<u>s</u>ee" and L-T-A condition for "<u>s</u>aw").

3.4.1.3. <u>Fundamental Frequency of the Test Passages.</u>

Fig. 31 shows mean fundamental frequency curves for the twelve repetitions of the test sentence under each of the eight experimental conditions. It can be seen clearly that all conditions except topical anaesthetic caused higher fundamental frequency than the normal, the maximum being reached under L-T and L-T-A conditions. In the two tonic syllables, <u>she</u> and <u>Shaw</u>, the difference in fundamental frequency between the normal and L-T-A condition were 28 c. p. s. and 32 c. p. s. respectively. The rise in fundamental frequency under conditions involving auditory masking agreed with Ringel and Steer (1963) and Ladefoged (1967a).

3.4.1.4. <u>First and Second Formant Frequencies of the Test Vocoids.</u>

Close observation of the means of the first and second formant levels for the four test vocoids [i] in "she", [i] in "see", [ɔ] in "Shaw" and [ɔ] in "saw" in all experimental conditions, show that the effect of auditory masking on the front vocoids is different from that on the back vocoids. As an illustration, Table 6 shows that the main effect of auditory masking on "s<u>ee</u>" is to <u>lower</u> the first and second formant frequency levels. For "s<u>aw</u>", however, the most noticeable effect

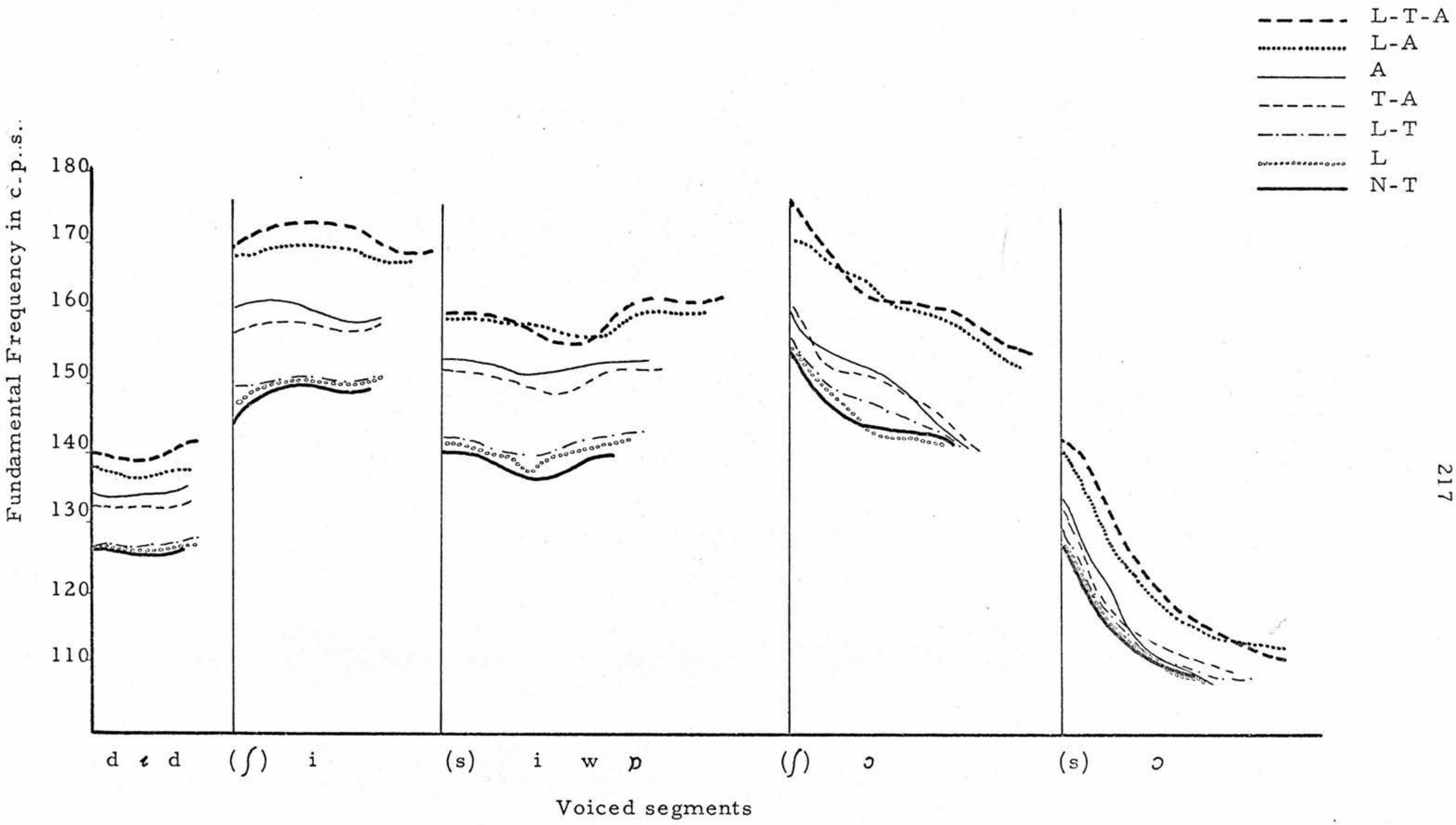


Fig. 31. Average fundamental frequency curves for twelve repetitions of the voiced segments under all experimental conditions. As the fundamental frequencies under N and T conditions were very similar, they are represented by a single line. The voiceless segments in the test passage are shown in brackets.

F1 of [i] in "see"		NO-A	A			NO-T	T			NO-T	T	
	NO-L	416.5	419.4	417.9	NO-L	412.7	423.1	417.9	NO-A	412.5	400.2	406.4
	L	396.2	383.3	389.8	L	405.8	373.7	389.8	A	406.0	396.7	401.4
		406.4	401.4	403.9		409.3	398.4	403.9		409.3	398.4	403.9
F2 of [i] in "see"		NO-A	A			NO-L	T			NO-T	T	
	NO-L	2,009	1,944	1,977	NO-L	1,990	1,964	1,977	NO-A	2,017	2,000	2,008
	L	2,007	1,932	1,970	L	1,985	1,954	1,970	A	1,958	1,918	1,938
		2,008	1,938	1,973		1,987	1,959	1,973		1,987	1,959	1,973
F1 of [ɔ] in "saw"		NO-A	A			NO-T	T			NO-T	T	
	NO-L	472.5	494.0	483.2	NO-L	490.4	476.0	483.2	NO-A	467.1	463.3	465.2
	L	457.9	499.8	478.9	L	480.8	476.9	478.9	A	504.2	489.6	496.9
		465.2	496.9	481.0		485.6	476.5	481.0		485.6	476.5	481.0
F2 of [ɔ] in "saw"		NO-A	A			NO-T	T			NO-T	T	
	NO-L	808.7	830.4	819.6	NO-L	824.6	814.6	819.6	NO-A	799.2	797.3	798.2
	L	787.7	825.0	806.4	L	810.4	802.3	806.4	A	835.8	819.6	827.7
		798.2	827.7	813.0		817.5	808.4	813.0		817.5	808.4	813.0

Table 6. Two-way tables of first and second formant frequency levels of [i] in "she" and [ɔ] in "saw". (Compiled from the means in Table 2 above).

under the A condition is for the first and second formant levels to rise. The situation was similar for "she" and "Shaw".

As mentioned in section 3. 3. 1., the tape-recordings of the test sentences under all experimental conditions were played to a number of trained phoneticians who made some informal auditory judgments on loudness, timing etc. They all agreed that under conditions involving auditory masking, particularly the L-A and L-T-A condition, there were significant increments in loudness level: in fact, during the L-T-A condition, the subject sounded as if he were almost shouting. In addition, the phoneticians noticed a general slowing down of tempo under most experimental conditions, particularly the L-T-A condition. This agrees with the quantitative measurements of duration (see section 3.4.1.2.).

3.4.2. Results of the Articulatory Measurements Taken from the Electropalatograph.

3.4.2.1. Maximum Area of Contact.

Table 7 shows the maximum areas of contact the tongue makes with the palate (expressed in terms of touched contact points) at any time during the six repetitions of the fricatives in the eight experimental conditions. The mean contact area for each experimental condition is included in the far right-hand column of the Table. These means are schematically presented in Fig. 32. The diagram clearly shows that for each fricative the greatest area of contact occurs under the L-T-A condition, with the least effect occurring under the T condition (except in [s] in "saw", where T is very slightly greater than L-A condition). The diagram also shows that three of the conditions involving lingual block (L-T, L-A and L-T-A) seem to have a consistently greater effect on area of contact than other conditions, for all the fricatives except "saw". In "saw" the conditions T-A and A seem more significant in producing a greater area of contact.

Table 7 shows that variability of contact area is greater in some conditions than others. (cf. results in section 3.4.1.) Variability of contact area was particularly noticeable for all the fricatives in

FRICATIVE	EXPERIMENTAL CONDITIONS	MAXIMUM TONGUE-PALATE CONTACT AREA						MEAN
		1	2	3	4	5	6	
[ʃ] in "she"	N	17	18	19	19	18	19	18.3
	T	18	19	22	19	18	22	19.6
	A	14	18	21	23	22	24	20.3
	T-A	19	20	24	22	24	22	21.5
	L	20	21	24	22	22	23	22
	L-T	19	24	18	22	19	20	20.3
	L-A	21	24	18	25	22	23	22.1
	L-T-A	22	25	28	28	28	23	25.6
[s] in "see"	N	20	21	22	20	22	21	21
	T	18	21	26	22	21	23	21.8
	A	15	23	23	20	21	25	21
	T-A	25	22	24	26	22	24	23.8
	L	21	25	27	22	24	22	23.5
	L-T	20	24	26	26	24	26	24.3
	L-A	21	25	24	26	26	24	24.3
	L-T-A	25	28	29	27	28	27	27.3
[ʃ] in "Shaw"	N	22	22	23	21	22	21	21.8
	T	21	22	23	20	23	22	21.8
	A	20	23	23	20	25	25	22.6
	T-A	24	22	22	26	24	23	24.5
	L	23	24	27	25	26	27	25.3
	L-T	22	26	24	27	22	26	24.5
	L-A	19	25	23	24	17	27	22.5
	L-T-A	24	29	31	28	26	26	27.3
[s] in "saw"	N	15	14	14	14	13	14	14
	T	15	16	12	15	12	18	14.6
	A	16	15	16	16	17	17	16.1
	T-A	18	19	18	18	16	20	18.3
	L	16	16	14	16	15	15	15.3
	L-T	17	14	15	14	16	16	15.3
	L-A	15	15	15	12	14	15	14.3
	L-T-A	23	21	20	16	18	21	19.7

Table 7. Maximum tongue-palate contact areas (expressed in terms of numbers of touched contact points on the artificial palate) for each of the six repetitions of the four test fricatives under the eight experimental conditions. The mean contact areas for each experimental condition are shown in the right-hand column.

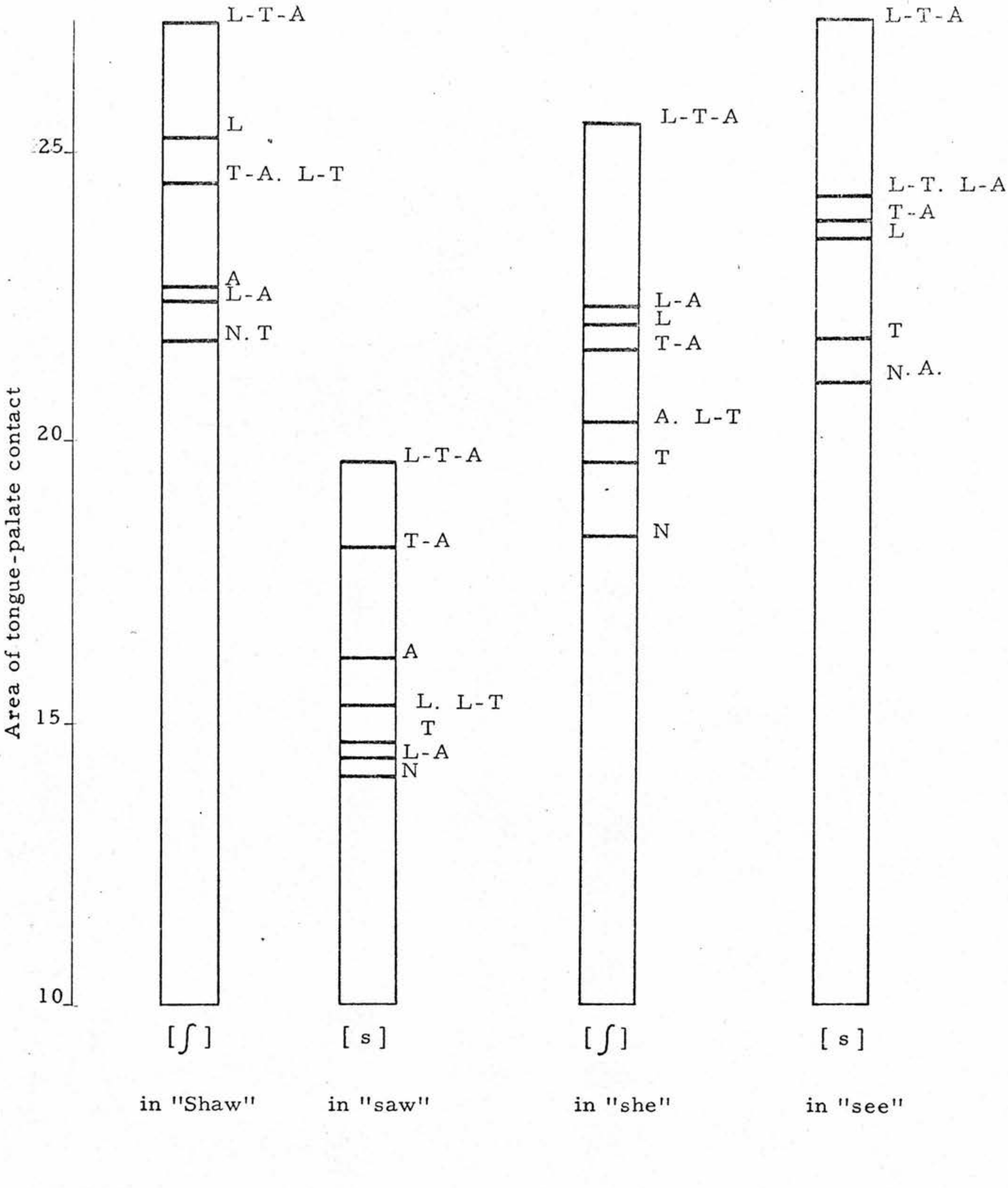


Fig. 32 Schematic representation of the maximum area of tongue-palate contact for each test fricative under the eight experimental conditions. The contact area is expressed in terms of the maximum numbers of contact points touched at any one time during articulation of the fricatives. Where the contact area is the same for two different experimental conditions, this is shown by a single line. (e.g. N and T in "<u>Sha</u>w")

the conditions involving auditory masking and in the combined L-T-A condition. Fig. 33 illustrates this variability with diagrams drawn from the EPG film frames for [s] in "saw" in two experimental conditions, N and L-T-A. Not only is the general pattern of contact different under the L-T-A conditions (e.g. contact is made further forward in the alveolar region and the central groove is narrower) but the inter-repetition variability in area of contact, measured in terms of the number of touched contact points, is clearly greater.

3.4.2.2. Narrowness of the Central Groove in the Alveolar Region.

The results of the measurements described in section 3.3.2.2. are shown in Figs. 34, 35, 36, 37. These graphs illustrate the mean change in the width of the central groove in the alveolar region for each of the four test fricatives during the eight experimental conditions. Each figure contains two graphs; the upper one shows those conditions with the least effects in narrowing the groove and the lower those conditions showing the greatest effect. The "groove-width curve" for the normal condition is shown in each graph as a basis for comparison. Where two conditions have very similar effects on the narrowness of groove, they are represented by a single line (e.g. L-T, T-A in Fig. 34).

The graphs clearly show that for each of the four fricatives, the narrowest groove occurs during the L-T-A condition (see the lower graph in each figure). The minimum groove-width possible (represented as 1 on the vertical axis, using the reference scheme outlined in section 3.3.2.2.) is reached during the articulation of "see" in the L-T-A condition. Not only, however, is the groove under the L-T-A condition always narrower, but the duration of the narrowed configuration also is greatest under this condition. The experimental conditions causing the next narrowest grooves are generally those involving lingual block e.g. L, L-A and L-T, although in one case, "see" (Fig. 34), condition A has more effect. For all the fricatives except "saw", condition T is closest to the normal. In "saw", the condition causing the least deviation from the normal is A.

The general shape of the graphs in Figs. 34, 35, 36 and 37 are

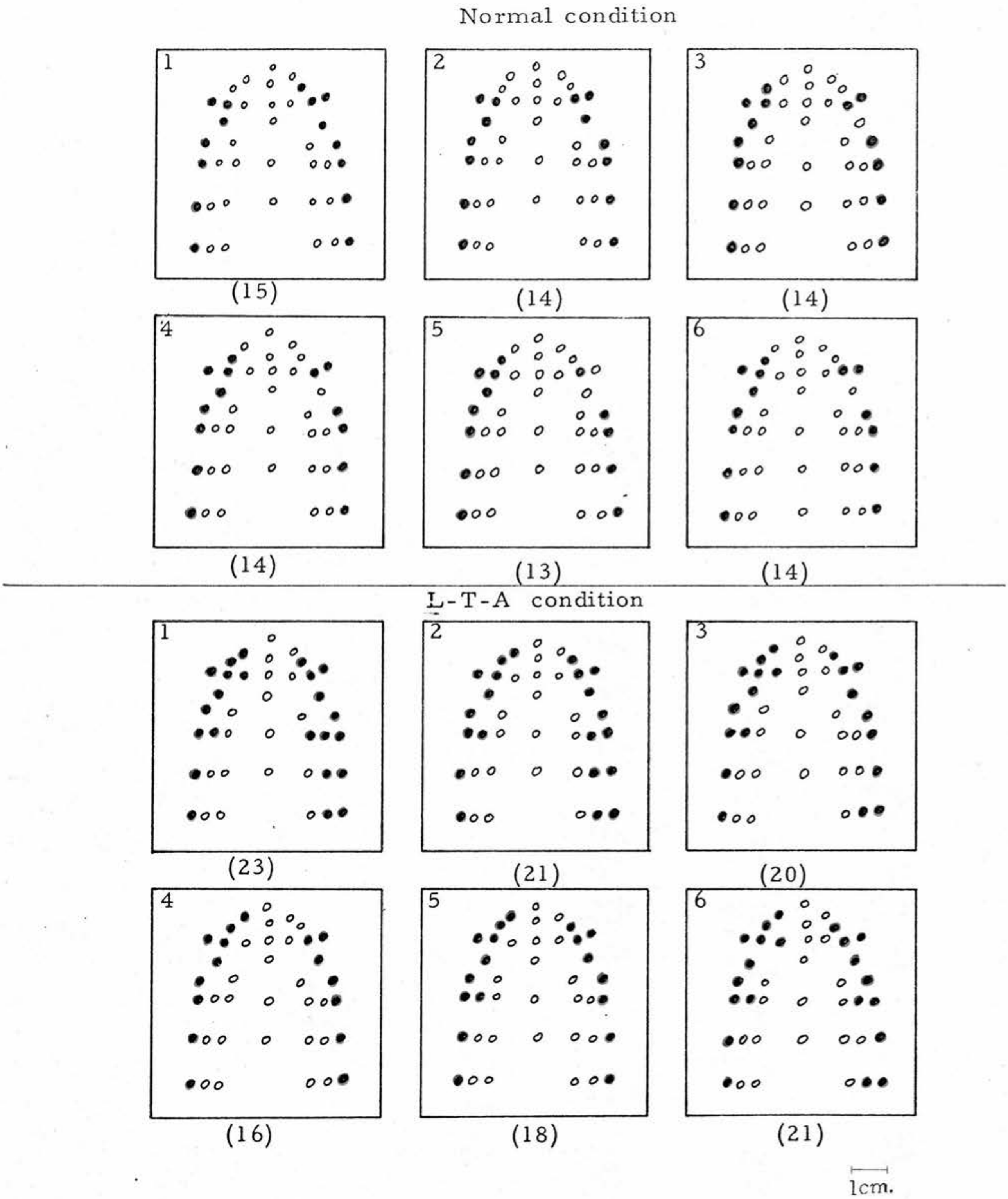


Fig. 33. Diagrams drawn from the electropalatograph display screen showing the inter-repetition variability of maximum tongue-palate contact area for the fricative [s] in "saw", under two experimental conditions N and L-T-A. The figures in brackets beneath each diagram show the total number of touched contact points for each repetition.

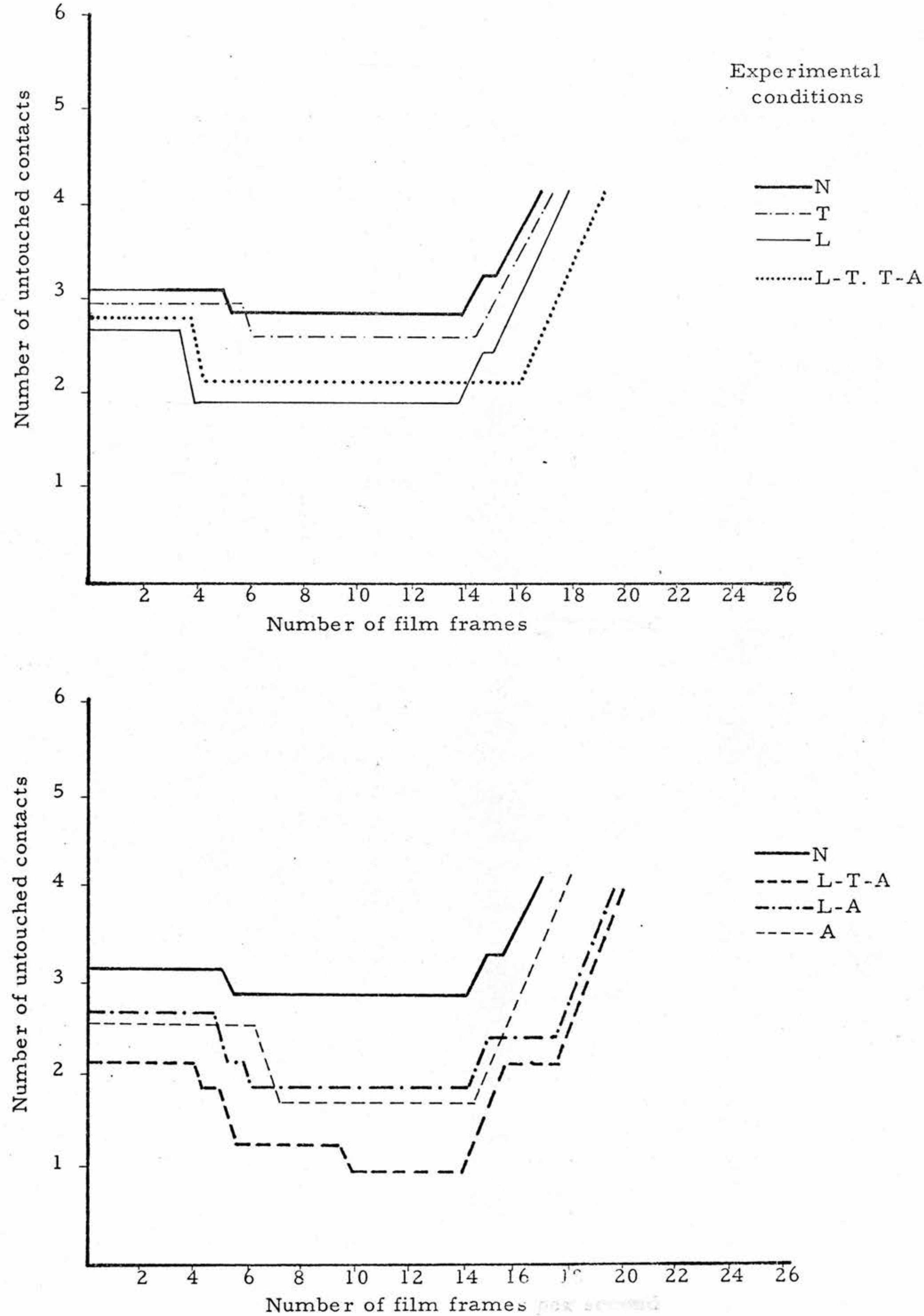
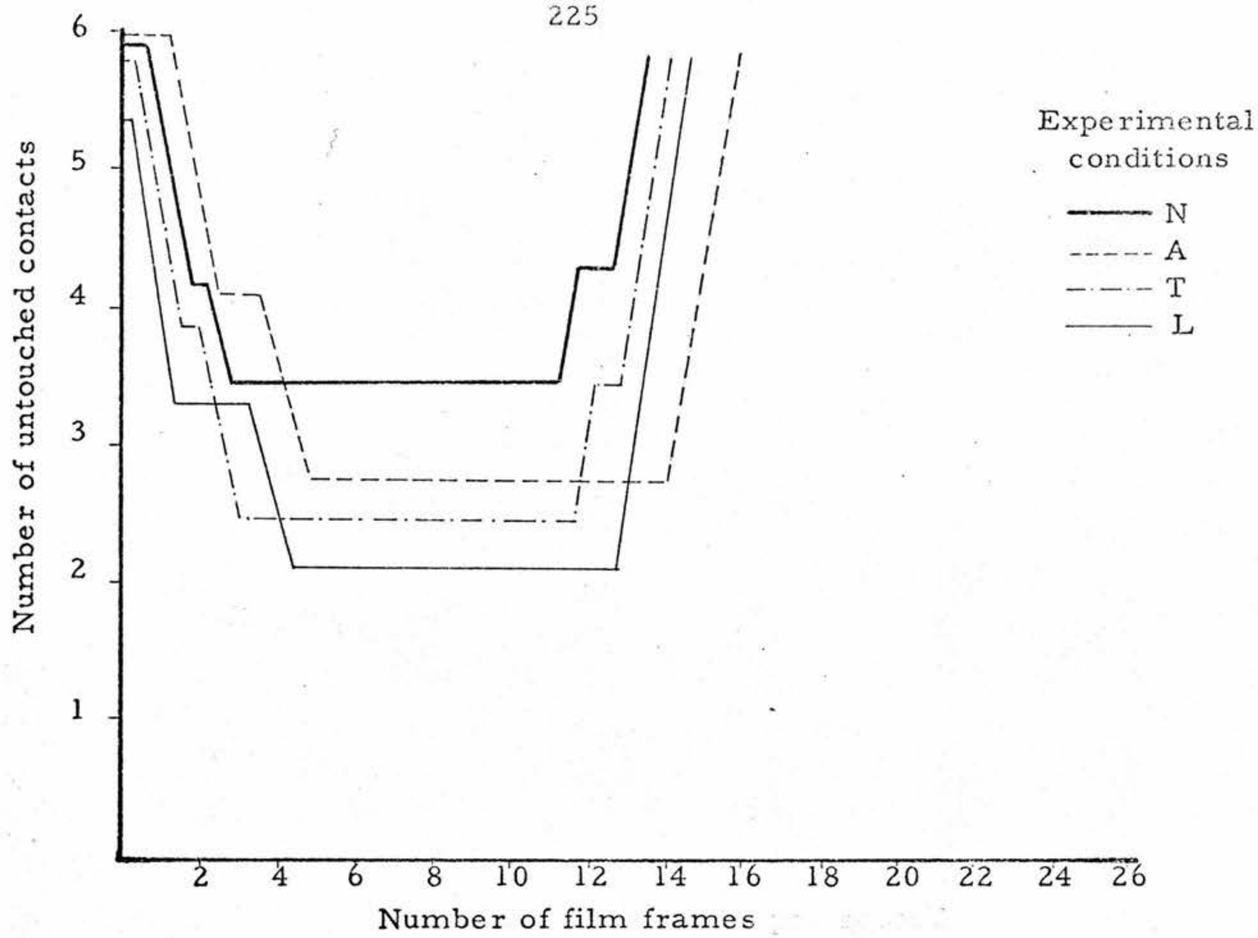


Fig. 34. Graphs illustrating the mean change in the width of the central groove of the tongue in the alveolar zone (see Fig. 30 for reference zoning scheme) during the articulation of the fricative "see" under the eight experimental conditions. Where the groove width curve is the same for two different experimental conditions (e.g. L-T and T-A) it is represented by a single line.



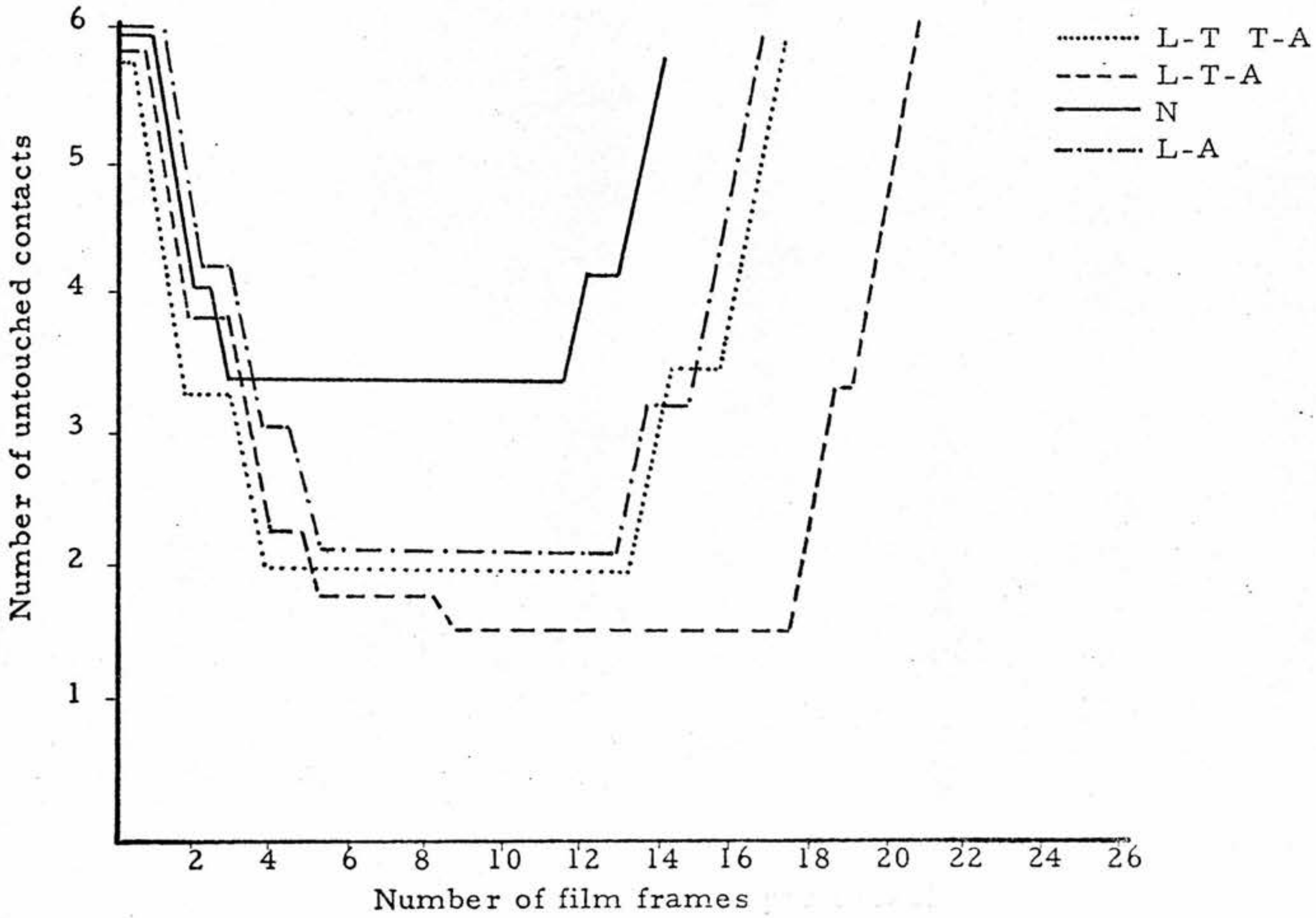
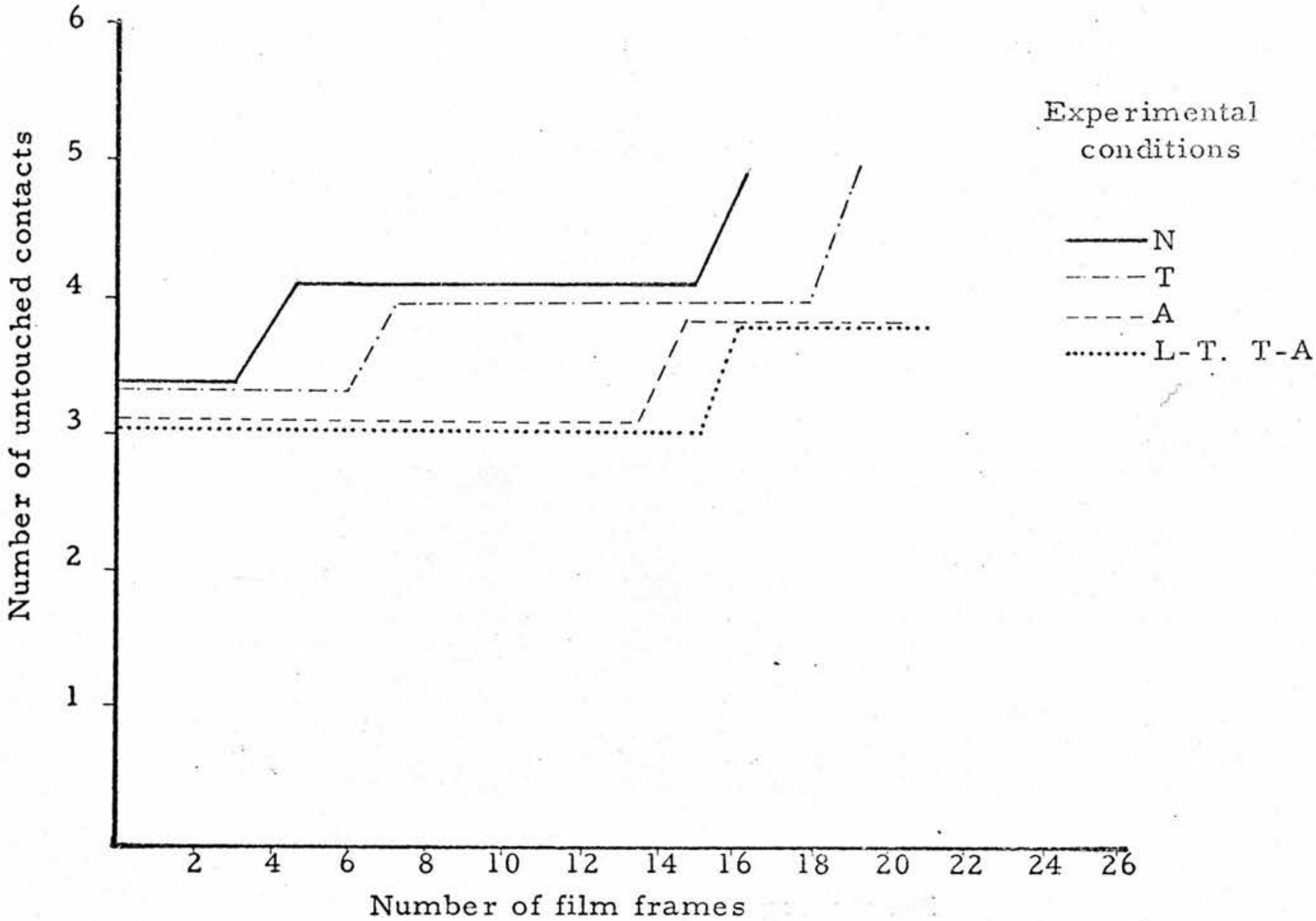


Fig. 35. Graphs illustrating the mean change in the width of the central groove of the tongue in the alveolar zone (see Fig. 30) during the articulation of the fricative "saw", under the eight experimental conditions.



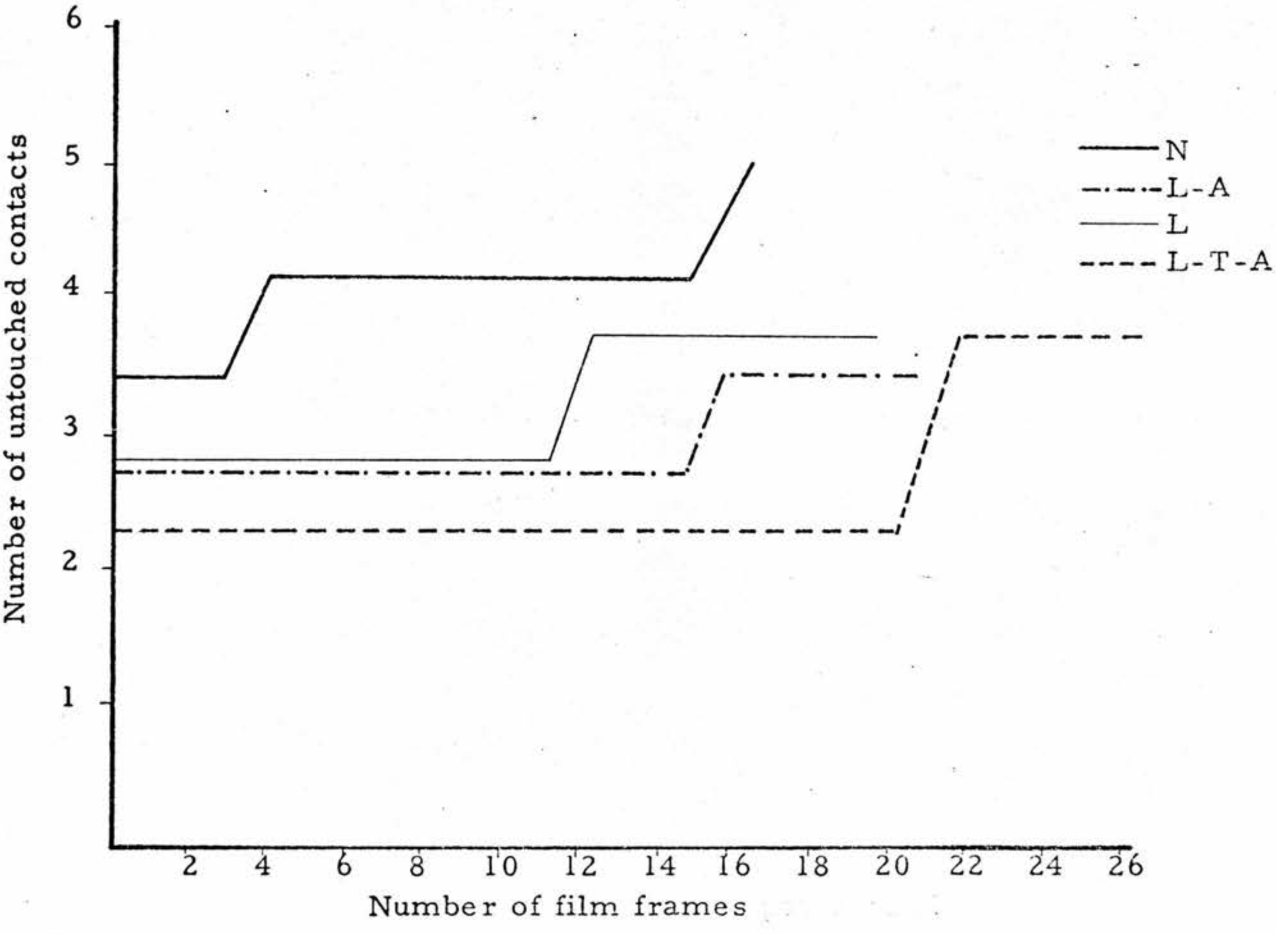
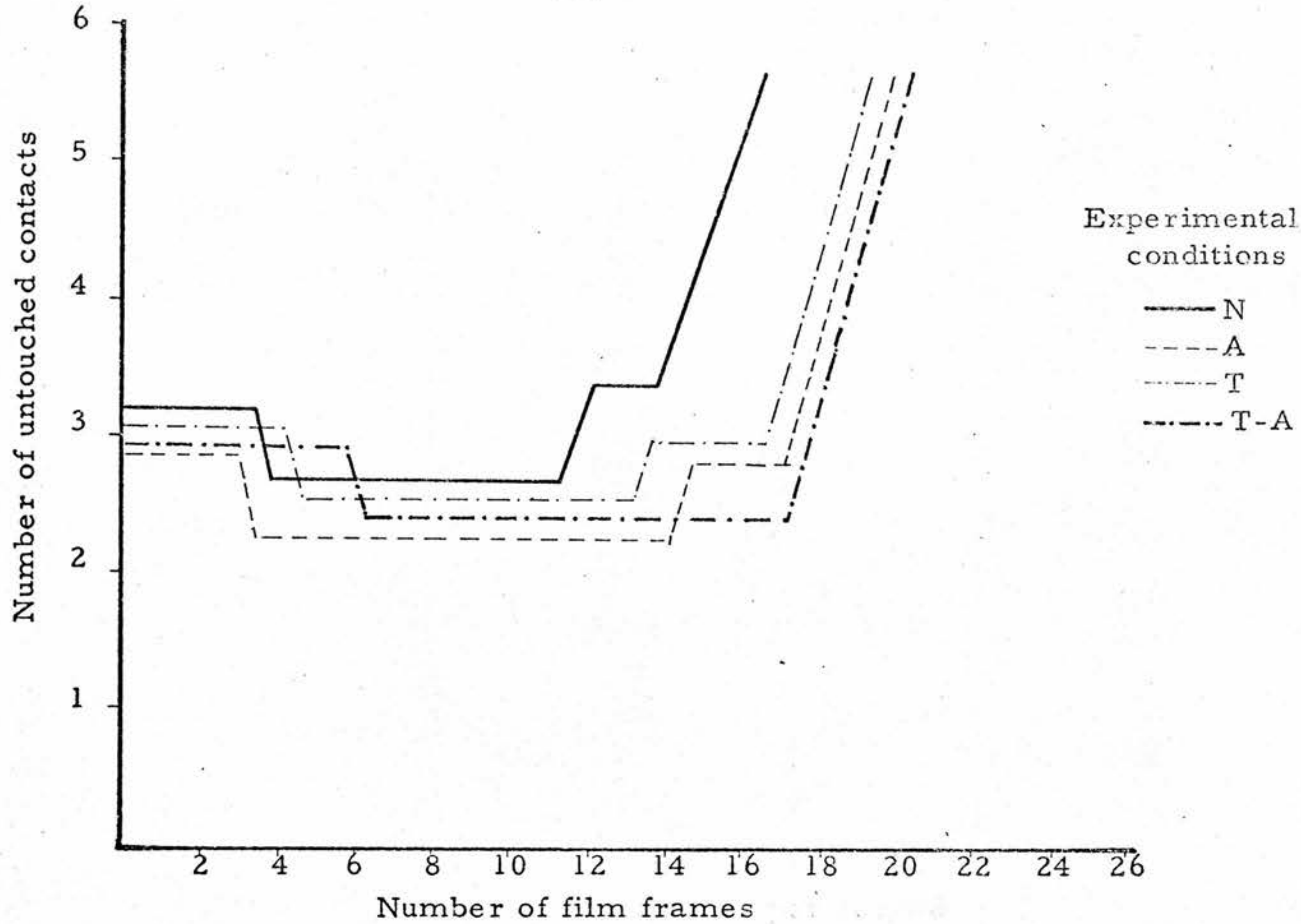


Fig. 36 Graphsillustrating the mean change in the width of the central groove of the tongue in the alveolar zone (see Fig. 30) during the articulation of the fricative "she" under the eight experimental conditions.



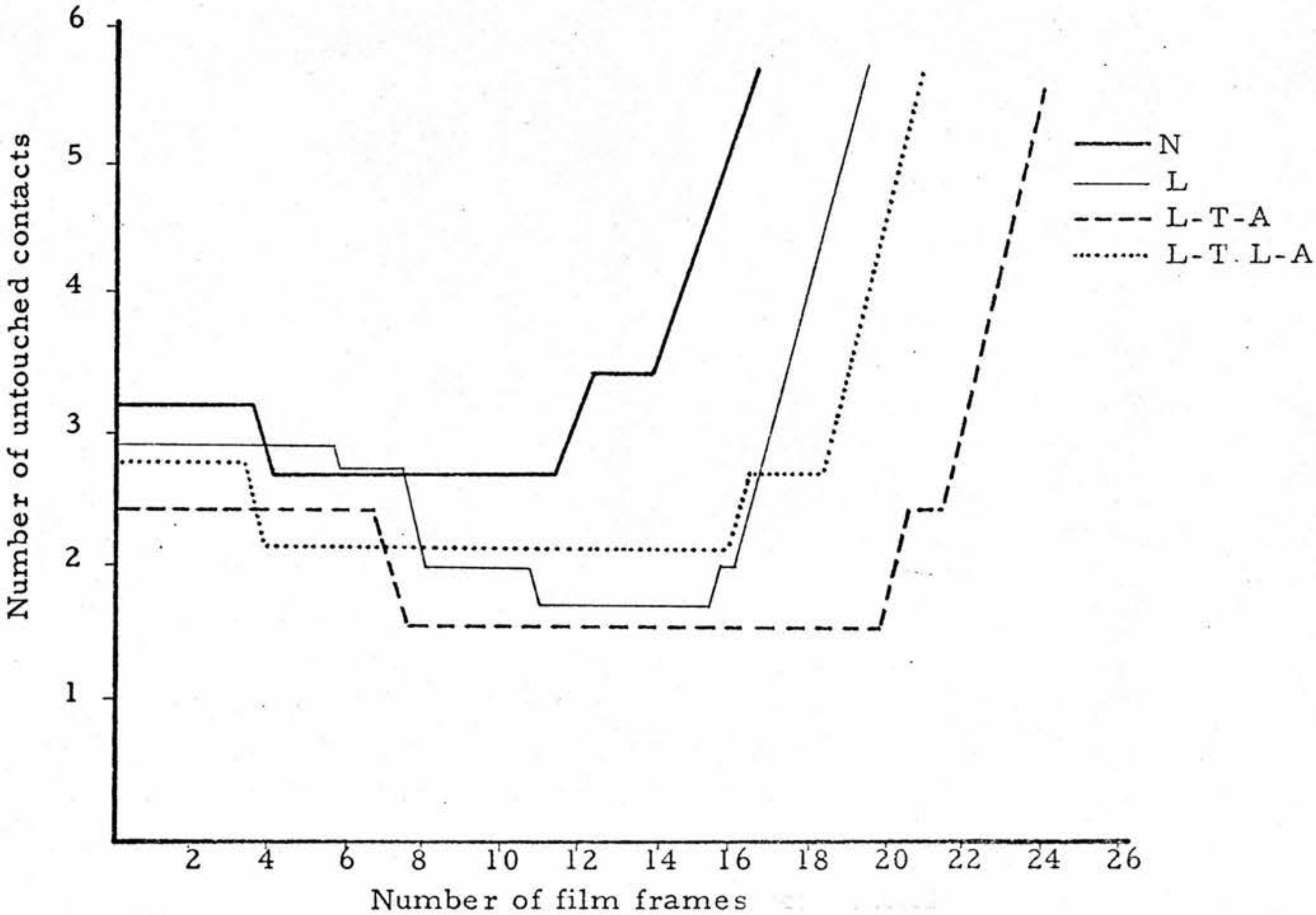


Fig. 37. Graphsillustrating the mean change in the width of the central groove of the tongue in the alveolar zone (see Fig. 30) during the articulation of the fricative "Shaw" under the eight experimental conditions.

slightly different. The graphs for [s] have more of a V-shape than for [ʃ]. This means that for the [s] in the test passage, the tongue starts with a fairly wide groove which narrows at approximately ten film frames from the beginning and widens towards the end. This final widening which leaves the tongue touching only the most lateral contact points is particularly noticeable in "saw" where the tongue is anticipating the following [ɔ]. Under most experimental conditions, the tongue reaches the minimum grooved configuration fairly rapidly, (usually after about six frames) for "she", "saw", and "Shaw". However, some conditions, particularly L-T-A, cause a delay as much as ten frames (e.g. in "see", Fig. 34) before reaching a configuration with minimum groove width. This phenomenon also occurs with conditions L in "Shaw" and L-A in "saw" (see Figs. 37 and 35), where the graphs show a step-wise progression to the maximally narrowed configuration.

It is interesting to note also that the grooves caused by condition L in both "see" and "Shaw" (see Figs 34 and 37) are narrower than those for L-T, although the total duration of the fricatives under the L-T condition is greater. The possible explanation for this phenomenon is discussed in section 4 below, and in Chapter 7.

3.4.2.3. Narrowness of Central Groove in the Palatal Region.

Graphs showing the narrowness of the groove in the palatal region were drawn using the procedure outlined in section 3.3.2.3. It was found that generally, for all four fricatives, the width of the groove here was directly proportional to that in the alveolar region; those conditions showing minimum width in the alveolar region also produced minimum width in the palatal region. Consequently, it was felt unnecessary to present these graphs in detail. As an illustration, however, Fig. 38 shows the mean groove-width curves for the six repetitions of the four fricatives in two experimental conditions, the normal and L-T-A. The graphs show clearly that the groove is narrower under the L-T-A condition. Also, the step-wise progression to the minimal grooved configuration noted in the previous section is quite evident here in "saw", "Shaw", and "she".

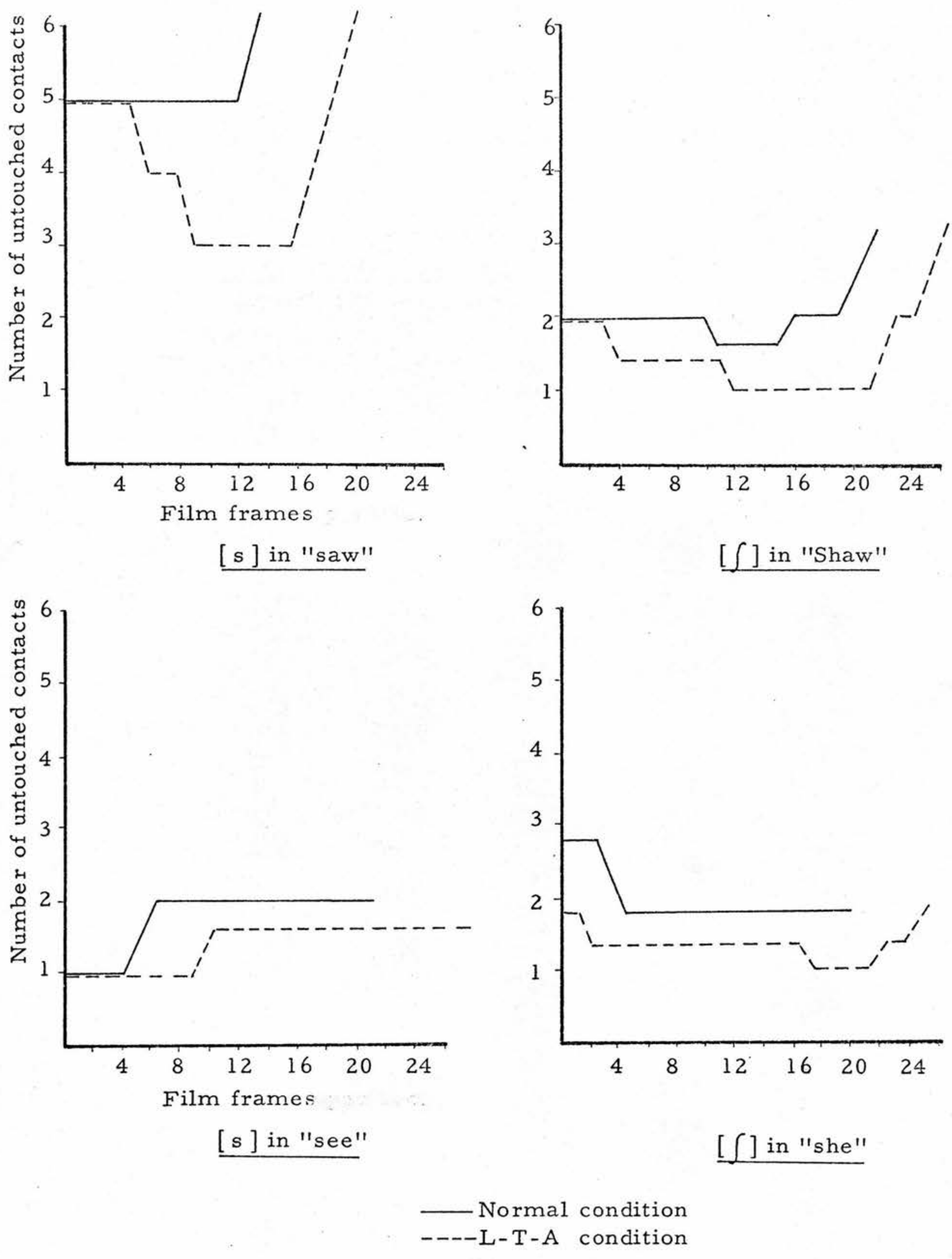


Fig. 38 Graphs showing the mean width of the central groove of the tongue in the palatal zone (see Fig. 30) during the articulation of the four fricatives "saw" "Shaw", "see" and "she" under two experimental conditions, the normal and L-T-A condition.

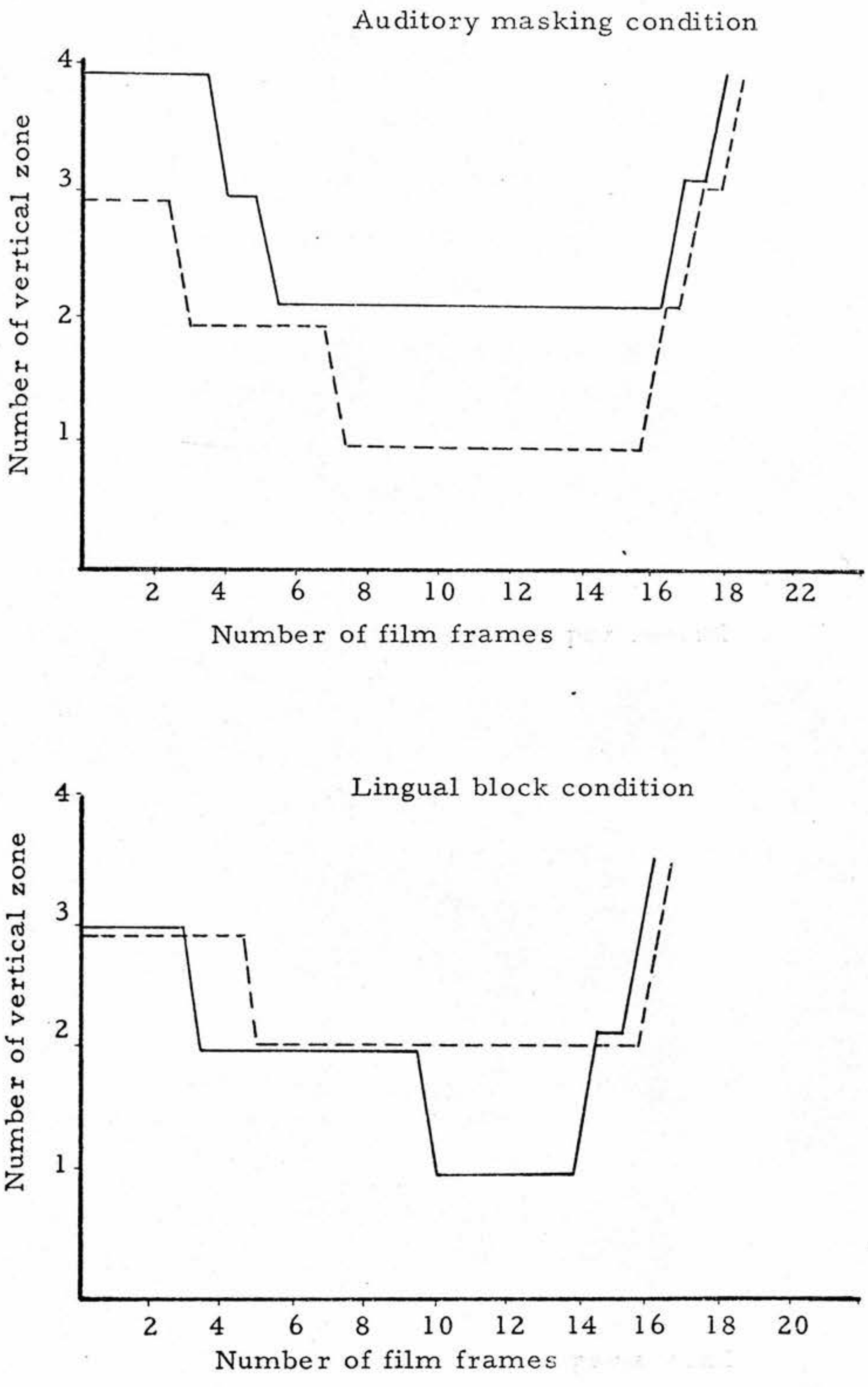
It is interesting to note that for "see", the point in time when the groove in the palatal region widens (i.e. 4 frames from the beginning in the normal condition, 9 in the L.T.A condition) corresponds closely to the time when narrowing of the groove in the alveolar region takes place. A possible physiological explanation for this is that in the articulation of "see", the tongue first makes contact laterally in the palatal region then moves up towards the alveolar region, where the lateral parts of the tip and blade articulate against the alveolar ridge and front incisors. As the tip presses onto the alveolar ridge, the post-alveolar groove widens.

3.4.2.4. Asymmetrical Movements of the Tongue.

The tracings from the film frames in Fig. 33 showed clearly that the tongue does not always make symmetrical contact with the palate during articulation of complex sounds such as the test fricatives. In order to represent this asymmetrical articulation, graphs were drawn illustrating the contact patterns of the right and left sides of the tongue using the technique described in section 3.3.2.4. Typical graphs for the fricative [s] in "saw" under both L and A conditions are shown in Figs. 39 and 40. Fig. 39 shows the changing contact patterns in the alveolar region; Fig. 40 shows the patterns for the palatal region. The left and right sides of the tongue are shown by unbroken and broken lines respectively.

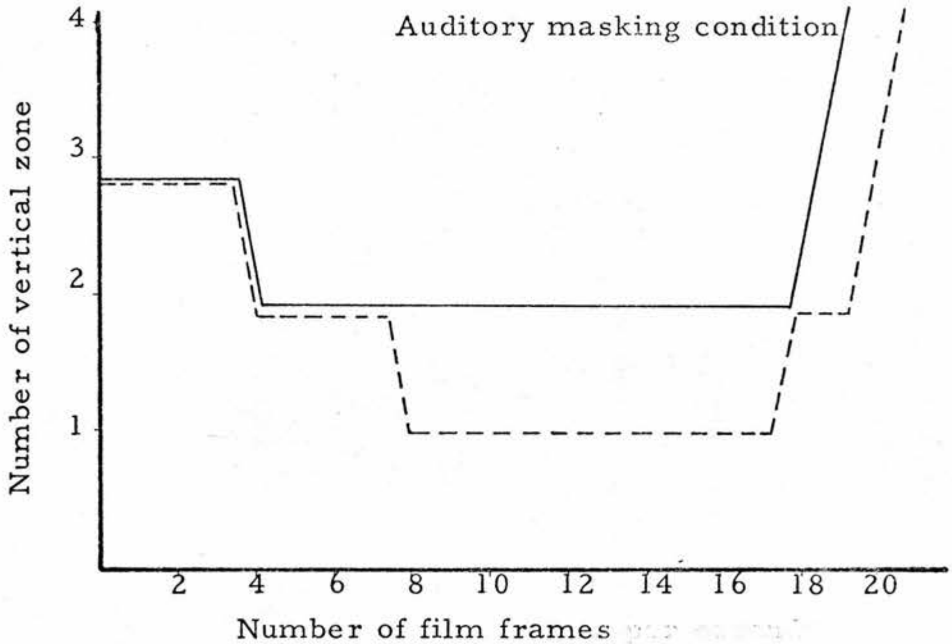
Figs. 39 and 40 clearly show the asymmetrical contact patterns of the tongue. Under the L condition, in both the alveolar and palatal planes, the left side of the tongue moves closer to the centre line of the palate during the fricative production. Under the A condition, however, the tongue moves closer to the centre on the right side. Observation of all the fricatives under conditions involving lingual blocks (particularly L and L-T) indicated this same tendency towards the left side of the palate whereas those conditions not involving lingual blocks (notably N, T, A and T-A) usually favoured the right. The possible explanation for this phenomenon is discussed below in section 4.

It seems clear from these results that the groove associated with

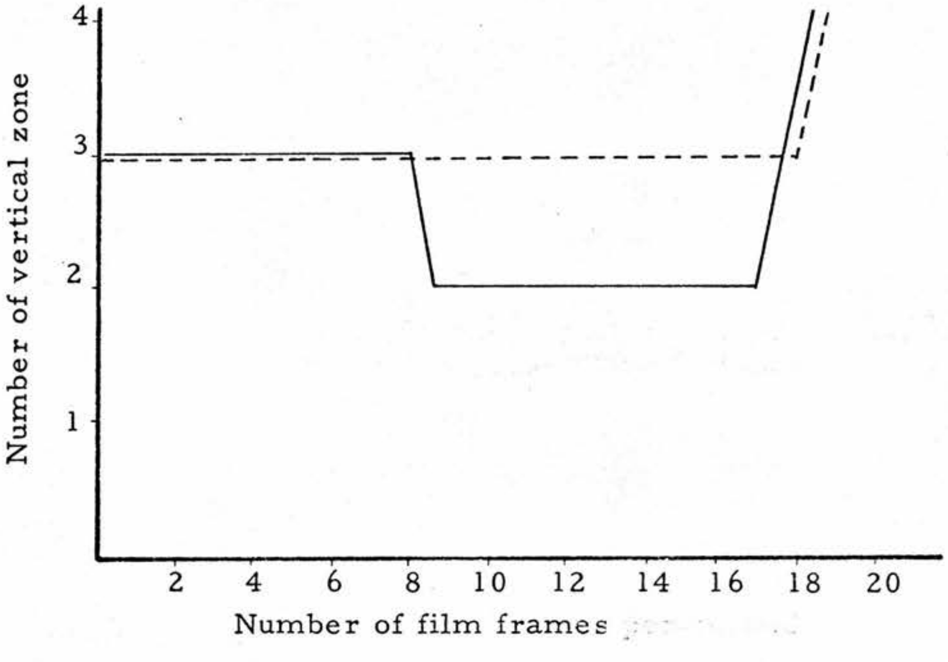


—— Left-hand side of tongue
---- Right-hand side of tongue

Fig. 39. Graphs showing asymmetrical tongue movement in the alveolar region during the articulation of the fricative "saw" under the auditory masking and lingual block conditions. For the vertical zoning scheme see Fig. 30 and section 3. 3. 2. 2.



Lingual block condition



——— Left-hand side of tongue
- - - - -Right-hand side of tongue

Fig. 40. Graphs showing asymmetrical tongue movement in the palatal region during the articulation of the fricative "saw", under the auditory masking and lingual block conditions. For the vertical zoning scheme, see Fig. 30 and section 3. 3. 2. 2.

the test fricatives is not usually symmetrically formed exactly in the centre of the palate. Rather it is situated slightly on one side of the centre line.

3.4.2.5. Forward Contact of the Tongue.

Observation of the EPG film for each of the fricatives showed that in some conditions the tongue moved further towards the front incisors than in the normal condition. This was particularly noticeable for "saw" under all conditions involving lingual blocks where contacts in horizontal zone number 1 were touched in all cases. For "see" contacts in zone 1 were touched in three of six cases in L, L-T, and L-A and in all six cases in L-T-A conditions.

3.4.3. Summary of Acoustic and Articulatory Results.

The main effects that alterations in sensory feedback resources have on the different speech output variables described in the previous sections are as follows:

1. Rise in the frequency level of fricatives "see" and "saw"; more variable effects for "she" and "Shaw" including lower frequency level under some conditions (e. g. T, A, L-T and L-A).

2. General increase in segment duration for contoids and some vocoids. Auditory masking seems to have more effect on the duration of low back vocoids (e. g. [ɔ]) than either the L or T conditions.

3. Rise in first and second formant frequency levels of [ɔ] under A conditions, but fall in levels for [i] under the same conditions. Slight fall in formant frequency of all test vocoids under T and L conditions.

4. Rise in fundamental frequency of test passage for all conditions other than T (maximum rise under L-T-A condition).

5. General increase in loudness level particularly under those conditions involving A.

6. Increased area of tongue contact with the palate (as defined in section 3.4.2.1.) particularly under conditions involving L (maximum under L-T-A condition).

7. General change in tongue configuration; narrowed central groove in the alveolar and palatal regions (narrowest groove for "s̲ee" in L-T-A condition). Relatively gradual approach (the "step-wise" progression, see section 3.4.2.2.) of the tongue to the position of narrowest configuration in some conditions (e.g. L-T-A and L for "S̲h̲aw" and L-A for "s̲ee").

8. Asymmetrical contact made by the tongue against the palate in the four test fricatives.

9. During articulation of the test fricatives, movement of the tongue further forward than the normal under most experimental conditions (particularly those involving L), thus making more contact in the region anterior to the "alveolar" plane.

10. Increased variability under most experimental conditions, especially L-T-A. Most significantly higher variances seen in the duration of the test fricatives.

3.5. Quantitative Testing Procedure to Assess the Degree of Sensory Deprivation.

As was indicated in section 1.3. above, in addition to measuring the effects of the eight experimental conditions on the various speech output variables, an attempt was made to quantify the relative attenuation that selective anaesthesia and auditory masking has on the sensitivity of sensory reception from the tongue. It was decided to use a testing device which aimed at assessing the "force-threshold" for applied stimuli to the tongue's surface under the different experimental conditions. It was hypothesized that this so-called force-threshold as measured by this device, would be considerably different under the topical anaesthetic and lingual block conditions, a higher threshold being associated with the block anaesthesia.

It was necessary to design and build a special aesthesiometer for the testing procedure as most commercially available force-measuring devices were unsuitable for use in the oral region. Those types of aesthesiometer using the classical "Von Frey hairs" principle (e. g. the Semmes-Weinstein nylon filament device made by Shaw Laboratories, Syosset, New York) have been used by some investigators (e. g. Kenshalo and Nafe, 1962; Grossman, 1967) for measuring force-thresholds, but there are a number of disadvantages associated with their use : it is difficult to quantify the force stimuli accurately; the operator is unable to control the stimulus onset time; and, because of the length of the fibres, they are difficult to manoeuvre successfully within the limited space of the oral cavity. The Edinburgh aesthesiometer was designed specially for use within the oral cavity and largely avoids the disadvantages of these other instruments.

3. 5. 1. Description of the Edinburgh Oral Aesthesiometer.

A schematic diagram of the instrument is shown in Fig. 41. There are three main parts : a metal supporting stand positioned in front of the subject; a moveable arm which slides up and down the upright part of the stand and can be fixed by means of an adjusting screw to any height on the stand; and a test probe unit consisting of a hollow metal container and a test probe lever. The test probe lever is freely mounted on a fulcrum inside the metal container, and is counter-balanced at one end by a fine spring. The exposed part of the lever ends in a small silver bulb which makes contact with the subject's tongue (see Fig. 41).

The whole test probe unit can be lowered downwards by means of an operating handle attached to the moveable arm. As the probe unit is lowered, the silver bulb encounters the surface of the tongue and the resistance causes the lever to move upwards. Calibrated weights can be hooked onto the lever to resist this upward movement, and so increase the force of the stimulus applied to the tongue.

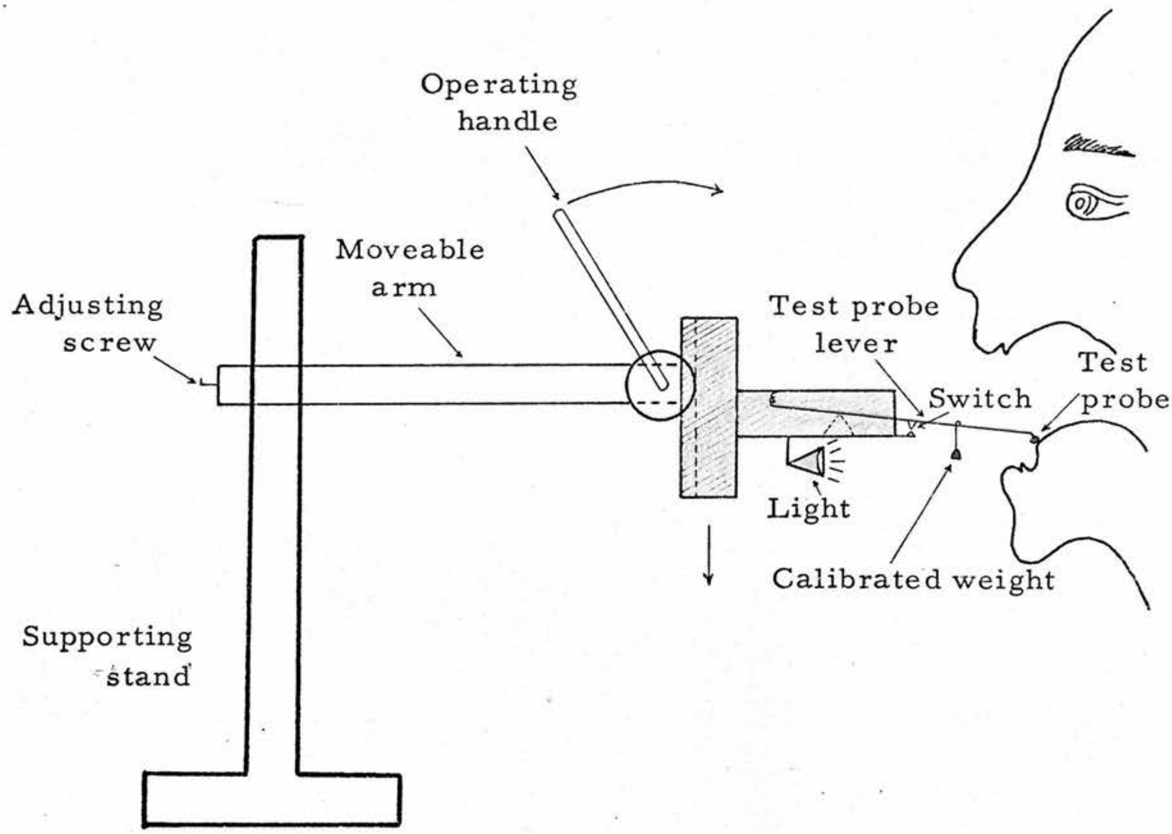


Fig. 41. Schematic diagram of the aesthesiometer used to determine the oral tactile force-threshold of the subject under each of the different experimental conditions.

For this experiment, the weights were calibrated in .25 gm. steps up to 10 gms. As the force exerted by the lever alone without any weights attached, is negligibly slight, because of the counter-spring inside the hollow container, the value of each calibrated weight represents fairly accurately the force applied to the tongue's surface. There is presumably a direct relationship between the force and the degree of deformation on the tongue's dorsum; the greater the force, the deeper the deformation.

Before the testing procedure commences, the subject is blindfolded and seated comfortably in front of the apparatus. The moveable arm is then adjusted so that the operator can lower the test lever onto the tongue (see Fig. 41). It is quite important to ensure the subject moves as little as possible when the stimulus is applied. The most successful form of head support found for this experiment proved to be a cushioned wooden support frame, on which the subject rests his chin (see Photograph No. 5, inside back cover). By allowing the whole weight of his head to rest on this frame, it is possible for the subject to remain relatively immobile, so that his tongue position does not move appreciably during the testing procedure. To apply the stimulus, the operator turns the operating handle (see Fig. 41) slowly in a clockwise direction. As soon as the probe touches the subject's tongue, an electrical circuit is completed and a green light flashes on a control panel situated in front of the operator. As the operator continues the smooth lowering movement the lever begins to lift, due to the resistance of the tongue surface. Immediately the lever lifts, a contact situated beneath the lever is broken (see Fig. 41) and another light, this time coloured red, flashes on the control panel. When the operator sees the red light, he turns the handle in an anti-clockwise direction, so raising the probe lever and removing the stimulus. By carefully watching the two lights, the operator is able to control to some extent the onset time of the stimulus. This is quite important, as some researchers (e.g. Nafe and Wagoner, 1941; Lele, Sinclair and Weddell, 1954; Kenshalo and Nafe, 1962) have noted that increased rates of application of tactile stimuli cause elevated thresholds.

Obviously, however, because the handle is manually operated, it is impossible using this instrument to guarantee that the onset times were exactly the same on separate applications of the stimulus.

As soon as the subject feels[1] the test probe on his tongue, he presses an indicator button in front of him to register a "yes" response. The outputs from this indicator switch and from the operator's control box are fed into a multi-channel mingograph so as to obtain permanent records of the subject's response time to the stimuli. In the first part of the testing procedure, a force-threshold for each experimental condition is estimated by a modified psychophysical "method of limits" test. The second part of the procedure aims at establishing a measure of the subject's sensitivity and response criterion, by means of a signal detection task. Both procedures will be discussed in detail.

3.5.2. Psychophysical Testing Procedure for Estimating Force-thresholds

To determine a force-threshold for each experimental condition, a modified psychophysical "limits" test was used (for a full discussion of this test, see Woodworth and Schlosberg, 1954). The method of limits was preferred to other psychophysical tests as it seemed the simplest and most direct method, and appeared the most appropriate to use with the oral aesthesiometer described above. Briefly, the testing procedure using the method of limits involves presenting the subject with a graded sequence of stimuli in a "descending" and "ascending" series, each series being carried far enough to locate the momentary transition point from one response category to another. Using the oral aesthesiometer, the procedure was as follows: The subject was instructed to report "yes" by pressing the indicator button in front of him, when he felt the test probe touching the tongue and "no" when he felt nothing. Table 8 shows the subject's responses to the different stimuli ("yes" = +, "no"= -). For each experimental condition, the experimenter began first with a stimulus

1. The subject has previously, by means of a trial run "tuned" himself to the type of signals that are to be detected. (see Galanter, 1962)

Stimulus (in ·25 gm. steps)	Lower Limit Tactile Sensation																							
	N(A) condition						T(T-A) condition						L(L-A) condition						L-T(L-T-A) condition					
	↑	↓	↑	↓	↑	↓	↑	↓	↑	↓	↑	↓	↑	↓	↑	↓	↑	↓	↑	↓	↑	↓	↑	↓
0	+	+	+	+	+	+	−	−	−	−	−	−												
1	+	+	+	+	+	+	−	−	−	−	−	−												
2	+	+	+	+	+	+	−	−	−	+	−	−	−	−	−	−	−	−						
3	+	+	+	+	+	+	+	+	+	+	+	+	−	−	−	−	−	−						
4	+	+	+	+	+	+	+	+	+	+	+	+	−	−	−	−	−	−						
5							+	+	+	+	+	+	−	−	−	−	−	−	−	−	−	−	−	−
6							+	+	+	+	+	+	−	−	−	−	−	+	−	−	−	−	−	−
7							+	+	+	+	+	+	−	+	−	+	−	+	−	−	−	−	−	−
8							+	+	+	+	+	+	+	+	+	+	+	+	−	−	−	−	−	−
9													+	+	+	+	+	+	−	−	−	−	−	−
10													+	+	+	+	+	+	−	+	−	−	−	−
11													+	+	+	+	+	+	−	+	−	−	−	+
12													+	+	+	+	+	+	+	+	−	+	−	+
13													+	+	+	+	+	+	+	+	+	+	+	+
14																			+	+	+	+	+	+
15																			+	+	+	+	+	+
16																			+	+	+	+	+	+
17																			+	+	+	+	+	+
18																			+	+	+	+	+	+
Threshold (T)	0	0	0	0	0	0	2·5	2·5	2·5	1·5	2·5	2·5	7·5	6·5	7·5	6·5	7·5	5·5	11·5	9·5	12·5	11·5	12·5	10·5
Average threshold (RL)	0						2.33						6.83						11.33					
S. D.	0						.41						.85						1.12					

t-values : $t_{N\text{ and }T}$ 13.71*
$t_{T\text{ and }L}$ 11.2*
$t_{L-T\text{ and }L}$ 7.5*

Table 8 The lower limits of tactile sensation for each ascending and descending series under each experimental condition. Figures at the foot of the table show the stimulus threshold (T) for each series, the average threshold (RL) per each experimental condition, standard deviations and t-values. Those t-values marked with an asterisk are significant at the 1% level.

clearly below the threshold (i.e. a negligibly slight force) (e.g. O for the Topical anaesthetic condition) and increased the applied force by .25 gm. steps until the subject reported "yes" (e.g. at 3 in the first column of the Topical anaesthetic condition). For this ascending series (marked ↑ in the Table), the stimulus force-threshold (written T) was arbitrarily regarded as lying somewhere between 2 and 3; it was taken as 2.5. (This method of estimating the threshold, T, is suggested by Woodworth and Schlosberg, 1954).

Next the experimenter started a descending series (represented in the Table as ↓) beginning well above the so-far indicated threshold T, and established a new threshold for this descending series. The ascending and descending tests were continued for each experimental condition until the experimenter was condifent he had obtained a reasonably reliable threshold. It can be seen from Table 8 that the stimulus thresholds for each ascending and descending series under any given experimental condition were not always identical. In the L and L-T conditions, the descending series showed consistently lower threshold values than the ascending series. This phenomenon is known as the "error of habituation" (Woodworth and Schlosberg, 1954). The primary object of the alternate ascending and descending series is to average out such errors in determining the mean stimulus threshold (called RL) for each experimental condition. The RL values for each experimental condition, found by averaging the T values, are shown at the foot of Table 8. It was found that auditory masking did not affect the sensitivity of the tongue as measured by the aesthesiometer so only those readings for the anaesthetic conditions are shown.

To assess the variability of the subject's performance, the Standard Deviations for each observation were calculated from the formula :

$$\sqrt{\frac{1}{5} \sum_{i=1}^{6} (T_i - RL)^2} \qquad \text{(see Table 8).}$$

A t-test was carried out to determine whether the stimulus thresholds for the anaesthetic conditions were significantly different from the normal and from each other. Table 8 shows the t-values for the pairs T and N, L and T, L and L-T. (If this $t > 2.447$ it is significant at the 5% level, if > 3.707 it is significant at the 1% level)[1]. It should be

1. These figures were obtained from Fischer, R.A., and Yates, F. (1957) : Statistical Tables for Biological, Agricultural and Medical Research (5th edn.) London. Oliver and Boyd.

emphasized that these t-values are probably larger than their real values because of certain methodological factors such as the small number of descending and ascending trials, the progression of the force-stimulus in discrete .25 gm. steps and the arbitrary means for deciding the stimulus thresholds for each descending and ascending series. However, because the t-values for these experimental conditions are so large, they are probably significant. It is reasonable to assume from these results, therefore, that topical and lingual block anaesthetic significantly alters the force-threshold for applied stimuli to the tongue as measured by the above procedure.

One can tentatively speculate on the neurophysiological reasons for this difference in threshold under the anaesthetic conditions. It was seen earlier in the discussion on the probable effects of anaesthetics on sensory receptors and tactile sensations, that topical anaesthetic plausibly affects the superficial free endings only, and does not penetrate to the deeper layers of the lamina propria, while lingual block probably affects the deeper organized receptors in addition to the free endings. Under the normal condition, light touch by the test probe (with no weights attached) is consistently felt, such sensation probably resulting mainly from stimulation of the free endings. However, under topical anaesthetic conditions, transmission of impulses from the free endings is eliminated, so this same light touch is not felt. But when the applied force is increased, so increasing the degree of deformation on the tongue dorsum, the deeper organized receptors may be stimulated, thus contributing to tactile sensation. This may account for the higher force-threshold under the topical anaesthetic condition. Under the lingual block conditions, where both the free endings and organized receptors in the lamina propria are affected, the applied force may have to be strong enough to stimulate the primary endings of muscle spindles (probably unaffected by lingual block) before tactile sensation is produced.

3.5.3. Signal Detection Task to Measure the Subject's Sensitivity and Response Criterion.

Psychophysical methods for determining sensory thresholds such as the method of limits described above, rely on the assumption that the probability that the subject will report the stimulus to be present, depends solely on his ability to detect the stimulus. Thus it is assumed that the subject will usually report "yes" when the stimulus is above a particular "threshold" and "no" when the stimulus is below it. Recent research on psychophysical testing procedures (e.g. by Galanter, 1962; Swets, 1961, 1964) however, has demonstrated that far more is involved than simply the sensitivity of the subject in discriminating between different stimuli. It appears that the decision of the subject to give a response to a stimulus depends not only on the physical nature of the stimulus being decoded by his senses, but also on his <u>criterion</u> of response. The subject's response criterion may be influenced by "background noise" which is "inherent in the environment, or is produced inadvertently by the experimenter's equipment for generating signals or is deliberately introduced by the experimenter or is simply a property of the sensory system" (Swets, 1961 : 169). It may also be influenced by the subject's motivation, and his "arousal level". Because of these different factors, often quite different decisions follow exactly the same stimulus even if the subject's sensitivity remains unchanged.

Signal detection procedures (see Swets, 1964 ; Green and Swets, 1966) enable us to quantify the subject's response criterion and so obtain a relatively pure measure of sensitivity. A measure of the response criterion is obtained by using a number of catch trials - randomly chosen trials that do not contain a signal - in the testing procedures. It has been demonstrated that the subjects frequently give a positive response to these catch trials. (Swets, 1961). The signal detection task thus differs from psychophysical procedures in one important respect; the observer does not know whether the signal is present or absent on any trial.

In the psychophysical testing procedure described above in section 3.5.2. it was seen how the subject was required to give either a "yes" or "no" response to the stimulus. It is much easier, however, to estimate the subject's sensitivity and response criterion if he rates his response according to a prearranged scale, with "yes" and "no" at the extreme ends of the scale (see Green and Swets, 1966 : 40). For the signal detection task in the present experiment, the subject used a category scaling method for estimating the magnitude of the force stimulus (see Galanter, 1962 : 142). He was instructed to judge the stimuli in terms of four categories: category 1 for the weakest stimuli and category 4 for the strongest, with the other two distributed between them in such a way that the intervals between categories were subjectively equal. To assist the subject in his response judgments a number of labels were proposed for these four categories : 1 = "sure no", 2 - "very slight sensation", 3 = "definitely something but not sharp," 4 = "definite sharp sensation." During the experiment the subject responded to the stimuli by pressing one of four keys corresponding to the four categories. Before the actual detection task, he was allowed to practise and so familiarize himself with the four response categories.

The experimenter used the same equipment for the signal detection task as was used for the psychophysical "limits" test. The stimuli presented for each experimental condition were the force threshold values estimated in the limits test. It was decided to present one hundred trials where a signal was present and one hundred catch trials, where no signal was present for each experimental condition. The subject was instructed to report for each trial.

It was intended to obtain a measure of the subject's sensitivity and response criterion for each experimental condition. Unfortunately, however, the subject began to develop immunity towards the lingual block anaesthetic. This probably occurred as a result of numerous insertions of the hypodermic needle over a period of time in the same position near the mandibular foramen. Possibly, slight inflammation caused by the needle resulted in a barrier of scar tissue which resisted the penetration of the anaesthetic solution. Consequently, following medical advice, it was decided not to complete the signal detection task.

It was possible, however, to obtain some results for the conditions involving topical anaesthesia and auditory masking. The subject's responses to the test trials in the A, T, and T-A conditions are shown in Appendix 2. The responses are summarized in Table 9 below:

	N Response Category				A Response Category				T Response Category				T-A Response Category			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Signal	-	-	-	100	-	-	10	90	4	16	28	52	1	10	34	55
No-Signal	100	-	-	-	100	-	-	-	90	10	-	-	90	10	-	-

Table 9. Responses for 100 signal-present and 100 signal-absent trials.

From two empirical quantities - the probability the subject will say "yes" when the signal is present, and the probability he will say "yes" when the signal is absent -one can calculate a value for d' (see Green and Swets, 1966) which is the measure of sensitivity for response category 2.

As there are no figures for response category 2 in both Normal and Auditory Masking conditions, it was only possible to determine d' for T and T-A conditions. The values of d' as calculated from Tables[1] are :

T condition - 3.032. T-A condition - 3.608

These values of d' are unusually high. The main reason for this is that the force stimulus used for each condition was probably too high, resulting in a strong bias towards the positive end of the scale in all conditions when the signal was present. It will be necessary to use a lower test threshold value in subsequent experiments to obtain a meaningful R O C curve for each experimental condition. (For a full discussion of the theory underlying the response characteristics see Green and Swets, 1966).

It is proposed in the near future to repeat the signal detection task for all conditions using lower force-stimuli as the test signals and defining the response categories a little more precisely. Hopefully it will then be possible to statistically compare the sensitivity and response characteristics for each experimental condition.

1. Freeman, P.R. (1964) : Tables of Values of d' and β unpublished report no. 529/64 M.R.C. Applied Psychology Unit, Cambridge.

4. INTERPRETATION OF THE ACOUSTIC AND ARTICULATORY RESULTS OF THE MAIN EXPERIMENT.

It seems from the results of the articulatory and acoustic measurements that the experimental conditions involving alteration in the feedback of sensory information by auditory masking and anaesthetic procedures have some (measureable) effects on speech performance. For all the speech output variables examined, most experimental conditions caused some changes to occur. It seems plausible therefore that, during speech production, afferent information from receptors in the oral region is indeed used to control ongoing motor performance (Hypothesis 1, section 2.4. above). The degree of importance of this sensory information is, however, difficult to assess. It is clear from listening to the tapes of the test passages, that speech is reasonably intelligible even under the condition involving maximal sensory deprivation (L-T-A condition). Most of the differences in articulation were allophonic changes; there were no cases of phonemic substitution. It is possible that the subject was able to rely on proprioceptive feedback which, as was seen earlier, may not be affected under the lingual block condition. If proprioceptive feedback had indeed been affected, one would probably have expected marked changes in quality of those articulations requiring positioning of the tongue without much contact being made with the palate and teeth, e.g. back vocoids in "saw" and "Shaw". However, the results show that the acoustic characteristics (as measured by F1 and F2 frequency levels) of these vocoids were only slightly altered under the lingual block conditions. Of course, one could not conclude from these results that lingual block does not affect proprioceptive feedback, but it does seem a reasonable hypothesis. As we saw in Chapter 2, the muscle spindles in the tongue may provide very sophisticated and economical means of controlling tongue articulation.

The question as to whether different types of sensory resources contributing to the feedback of sensory information play different roles in controlling speech performance is quite complex. There does seem, however, some slight indication from the duration data (see section 3.4.1.2 that auditory feedback plays a more important role than tactile feedback in the control of timing of those articulations involving small areas of tongue contact with the palate (e.g. the low back vocoids in "Shaw" or "saw"). Again, in the analysis of formant levels for vocoids, A was the condition which seemed to have most noticeable effect, causing a rise in formant frequency levels in [ɔ] and a fall in [i]. One may perhaps conclude from this that certain types of articulations particularly those involving small areas of tongue-palate contact (e.g. low back vocoids) depend more on auditory than on tactile monitoring. However, as seen above, results such as these involving comparisons of means should be regarded with caution, because of the very different variances under some of the sensory deprivation conditions, particularly those involving auditory masking.

Although there seems some indication that auditory feedback may play a more important role than tactile in the control of certain vocoids, it seems plausible that some aspects of the articulation of complex fricatives depend on both types of feedback. In Chapter 5 it was suggested that articulations such as [s] and [ʃ] are <u>complex</u> articulations requiring considerable delicacy of control facilitated by the transmission of neural impulses from the rich supply of sensory receptors in the front part of the tongue. So one would expect the articulations of [s] and [ʃ] to be considerably modified under sensory deprivation conditions. The results show that the main effect of most of the experimental conditions was a general "overshooting" of the articulatory targets for [s] and [ʃ]. This overshooting took the form of increased duration, higher frequency level, (mainly in [s]), greater area of tongue-palate contact, narrowing of the central groove and more forward movement of the tongue. As mentioned earlier (section 2.3.3.), some of these effects can be explained by increase pressure being everted by the tongue against the palate under some sensory deprivation conditions. This would have the effect of narrowing the central groove for the fricative in both the alveolar and palatal regions (see results in section 3.4.2.2. and 3.4.2.3.)

and also probably cause the rise in frequency levels for [s]. It seems plausible also that increase in muscular effort may account for the general increase in loudness level under most experimental conditions and also the rise in fundamental frequency. (The reason why most of these effects seemed more noticeable in [s] than in [ʃ] is probably due to the fact that the main part of the tongue-palate contact for [ʃ] occurs in the palatal and post-palatal region and as such may not be as affected under the lingual block which altered sensation primarily in the front two-thirds of the tongue.)

Why in fact does this "overshooting" occur? A possible explanation may lie in the notion of "pre-tuned" schemas outlined in Chapter 2, section 1.3.3. and in section 2.4. above. It was seen how the C.N.S. probably needs a certain pre-determined "amount" of sensory information during the execution of a planned articulation. If the receptors are inhibited, for example, under the lingual block conditions this information will not be received and steps may be taken in an attempt to bring into operation more receptors. Physiologically speaking, as far as tongue articulation is concerned, this may come about in three ways:- by forcing the tongue closer to the palate; by increasing the duration of contact; or by making the contact further forward in the mouth. The acoustic and articulatory results of this experiment suggest that all three ways may be employed.

Evidence that the tongue moves closer to the palate is provided by the electropalatograph measurements of the narrowness of the central groove for the four test fricatives. The results show that under most of the experimental conditions the central groove narrows during the release phase of the fricative in an attempt presumably to bring into operation more sensory receptors including both the free-endings and deeper organised endings. One would expect from the results of the sensory testing procedures (see section 3.5.) that experimental conditions involving lingual block would have a greater effect on tactile receptors than those involving topical anaesthesia, so the "overshooting" effects would be more pronounced under L conditions. The results illustrate this. Also it is interesting to note that in its asymmetrical articulation, the tongue makes more contact than the normal on the left side under L, and on the right side under A.

The second way that the C. N. S. may attempt to obtain more sensory information is to prolong the period of contact made by the tongue against the palate during production of the test articulations. As indicated in Chapter 2, some receptors, particularly the organised receptors in the deeper layers of the lamina propria, may continue transmitting neural impulses as long as the tongue touches the palate and teeth and cease transmitting immediately the tongue leaves the palate. Now the C. N. S. may have learnt to associate impulses from these receptors with particular articulations, presumably those involving relatively large areas of tongue-palate contact, and when information is not received from these receptors (for instance under L conditions) a reflex mechanism may cause prolonged contact in much the same way as was the case with increased effort discussed above. (For a more detailed discussion of this so-called reflex mechanism see Chapter 7). One would expect, therefore, increased duration of most test segments under lingual block conditions. Table 3 shows that duration is increased not only under lingual block conditions, but also under those conditions involving topical anaesthesia and auditory masking.

Another way of obtaining increased sensory information is to move the tongue further forward in the mouth, making contact nearer the front incisors, thus bringing into operation more receptors from the richly endowed region near the tip (see Chapter 2 for a discussion of the distribution of sensory resources in the tongue). The forward movement was particularly noticeable in the electropalatographic data of the test fricatives under those conditions involving lingual block (see section 3. 4. 2. 5.).

It is plausible that the C. N. S. can employ any one of these three different procedures for obtaining the necessary predetermined "amount" of sensory feedback. Thus an attempt may be made either to narrow the central groove or to prolong the contact, in, for instance, the articulation of [s] under the lingual block or L-T conditions. As seen in section 3.4.2.2. one would probably expect a narrower groove under the L-T condition, because there is hypothesized greater sensory deprivation (see section 3.5.). What happens, however, is that the groove under the L condition is narrower than under the L-T condition, although the duration of the contact under the latter condition is greater. Thus by means of these two different procedures, i.e. narrowing of the groove or increasing the duration, the C.N.S. may be trying to obtain the same quantity of sensory feedback information.

The variance figures in Tables 2 and 3 show that there is considerable variability in some aspects of articulation such as duration, fricative frequency, formant frequency levels for vocoids and tongue configuration (width of groove etc.) under most of the experimental conditions. It appears from the duration measurements that variability is greater for the test fricatives than for the vocoids. The maximum variances usually occur under the L-T-A condition with those conditions involving auditory masking also causing mostly significantly higher variances than the normals. It seems therefore, from these results, that some of the sensory information blocked by the anaesthetic normally plays a specific role in controlling not only the precise tongue configurations but also the timing of ongoing fricative production.

Most of the interpretations of the results of this experiment can only be very tentative. As seen earlier, we are still a long way from understanding the precise effect anesthetic procedures have on particular receptors. Also, we have little idea of the variability of anaesthetic effects on different occasions. There was a surprising similarity, however, between the results obtained on both replications of the experiment (see Appendix 1) so it may be possible after all to reproduce almost exactly the same anaesthetic effect if care is taken in carefully controlling the experiment.

Another limitation of the experiment is that only one subject was used. This meant that because of the different variances in the data under different experimental conditions, it was difficult to estimate an adequate experimental error. Standard comparisons of means by analysis of variance tests were therefore not possible. It is proposed in a later experiment, to extend the range of this experiment by using many more subjects and by investigating many more aspects of speech production.

CHAPTER 7

SOME ASPECTS OF A PRELIMINARY MODEL OF SPEECH PERFORMANCE.

1. GENERAL OUTLINE OF MODEL.

The results of the experiment described in the previous Chapter show clearly that interference with normal sensory feedback by the experimental techniques of anaesthesia and high intensity masking causes some sort of reorganisation of the speech production process. This reorganisation was seen to involve alteration of certain acoustic and articulatory features such as duration, fundamental frequency, vowel formant frequency levels, place of articulation etc. The electropalatographic data illustrated clearly that, during the articulation of fricatives [s] and [ʃ], the tongue behaved differently from the normal under the sensory alteration conditions (see Chapter 6, section 3.4.2.). It was also seen that most articulatory and acoustic features of the test vocoids and contoids (particularly the fricatives) showed more variability between successive repetitions under the feedback deprivation conditions than in the normal condition. It was suggested consequently, that for certain aspects of speech at least, some of the sensory information altered by the experimental procedures plays an important role in the ongoing control of speech. This Chapter will examine certain of the functions the nervous system may perform in generating an utterance, and in controlling its myodynamic performance by means of sensory feedback channels.

It must be emphasised at the outset that most of the arguments put forward in this Chapter are extremely speculative in the absence of any comprehensive direct experimental data concerning neuro-physiological activities during speech. We can, however, infer certain of the functional properties of the central controlling systems in the brain by a close examination of the output i.e. the speech articulation itself, both under normal conditions and when altered experimentally as in this experiment. (The research strategy, which infers properties of an inaccessible control system from the output is widely accepted in scientific investigations (see Beveridge, 1961, quoted by Laver, 1970)). So, although we are learning more and more about the peripheral chain in the speech production process, e.g. the contractions of muscles and their accompanying movements, by means of investigations involving sophisticated instrumentation such as electropalatography, electromyography and cinefluorography, what we can say about the central control system is still rather speculative.

In this Chapter we will be primarily concerned with how the motor execution of a speech utterance is controlled rather than how the utterance itself is generated in the C.N.S. However, it is useful firstly to outline briefly some of the possible functional activities of the brain in the initiation and generation process. Fig. 42 shows a simplest possible block diagram illustrating some of the functional activities of the central and peripheral nervous systems in producing and controlling a speech utterance. Broadly speaking, the model of speech performance presented here is basically similar to that described by Laver (1970). There are, however, a number of differences, which will be indicated in the course of the discussion. One can hypothesise the presence of at least three major functions: a central or control function, which takes place probably at the level of the cortex, a motor execution function, which takes place at the periphery of the body i.e. at the level of muscular contractions and the accompanying movements of the speech organs, and a feedback function, operating both within the brain and at the periphery. During the control function of a speech utterance, there are probably at least three main processes involved: the initiation of an idea or intention on the part of the speaker to say something; (Laver (1970 : 62) is a little more specific about this ideation process, which he regards as "initiating the approximate semantic content of any verbal message the speaker wishes to communicate."); the formulation of a neurolinguistic programme appropriate for the expression of the idea (Laver (1970) calls this the planning process); and the co-ordination or regulation process, which translates the motor aspects of the programme into a sequence of motor commands to the muscles. During the motor execution function, the following processes take place: transmission of the motor impulses at the neuromuscular junctions of muscle fibres (see Chapter 2, section1.1.4.2.), mechanical contractions of the muscles, and resulting movements of the speech organs. The feedback function involves the following: feedback of sensory information from the periphery, comparison of what actually

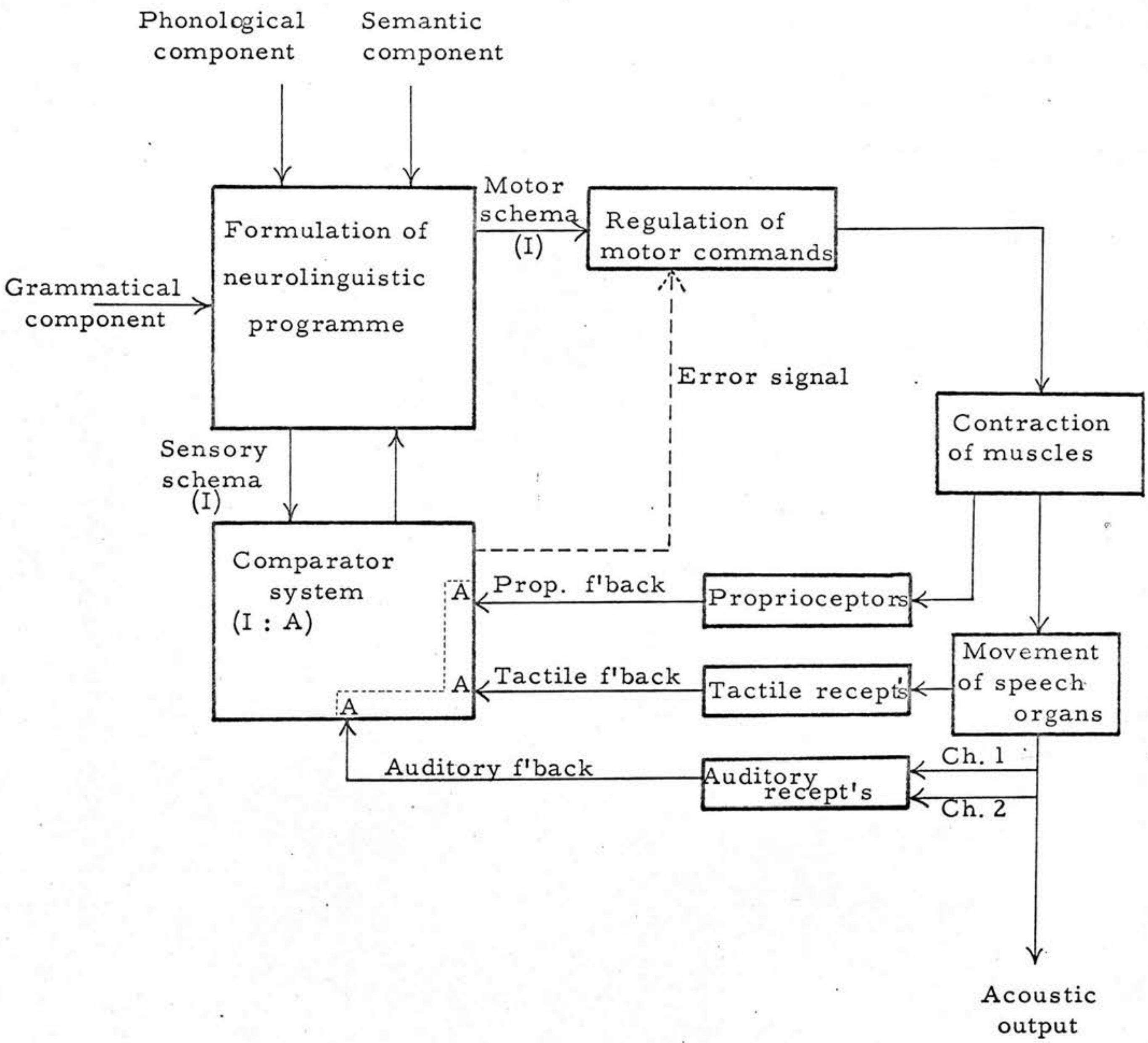


Fig. 42. Simplest possible block diagram showing some of the functional activities of the central and the peripheral nervous system during sensori-motor control of speech articulation.

obtains at the periphery with what is intended in the neurolinguistic programme, and regulation of the motor commands to the muscles according to the difference between the actual and intended situation. It will already be clear from this that the view put forward here regards the speech control system as being a predominantly closed-loop system i.e. one in which continuous sensory feedback plays an essential role in the controlling function. Arguments in favour of such a system over a predominantly open-loop system will be discussed later.

1.1. Formulation of the Neurolinguistic Programme

Firstly, a few general comments about the central control function and its principal activity, the formulation of a neurolinguistic programme. In discussing the co-ordination and regulation of any bodily movements, it is useful at the outset to regard every purposeful act such as opening a door or making a speech articulation as arising from what Bernstein (1967) calls a "motor problem" and is determined by the situation as a whole. In attempting to solve the motor problem, the individual is guided by a wealth of information arising from such factors as knowledge of what happened in the past and is likely to happen in the future, as well as multifarious information from the sensory organs concerning many aspects of the individual's relationship with the outside world, ranging from the particular social environment to the position of the vocal organs etc. Perhaps the most important guiding principle for the solution of the motor problem is the "image" or "representation" of the result of any action the individual might make, although we know very little about the neural correlates of this "image of the future" (for a more detailed discussion, see Bernstein, 1967:147). On the basis of all this information, the individual attempts to formulate an optimal strategy or "plan" for solving the motor problem. Exactly how we go about formulating this plan is at present not known. What we do know, however, is that, although at first when we meet a particular motor problem we may be faced with a great number of alternative plans, after some practice in the process of solving the motor problem, a particular optimal plan becomes preferred to all others. As far as speech articulation is concerned, the formulation of the neurolinguistic programme can be regarded as the attempted solution to the central motor problem. In linguistic terms it can be regarded as a sort of blueprint for the semantic, grammatical and phonological aspects of the speech utterance. Although the phonological aspects of the programme are the main concern of this section, it is useful to hypothesise on the semantic and grammatical components as well.

As far as the semantic content of the programme is concerned, this is probably selected from some sort of lexical storage system. (For a discussion as to how neurolinguistic information may be stored, see Laver, (1970 : 63)). Evidence from slips of the tongue such as "sleast" (reported by Laver, 1970) where there is confusion between "least" and "slightest" suggests that more lexical items are "activated" or "primed" than are ultimately selected for the neurolinguistic programme. As Lashley (1951) says: "There are indications that, prior to the internal or overt enunciation of the sentence, an aggregate of word units is partially activated or readied" (p. 155). What can we say about the selection process? Obviously, in the search for the optimum lexical unit some sort of monitoring process must take place, in which a number of competing items will be compared for suitability in expressing the original idea. The coarseness of the monitoring process, incidentally, may depend on the time at the individual's disposal. If he is under time pressure, presumably the monitoring process may be more cursory. Thus, one would probably expect more lexical slips to occur in rapid, hurried speech than in slow, deliberate articulation.

The procedures involved in selecting the appropriate item from the lexical store can be regarded as a problem in information - retrieval (see Laver, 1970). Some sort of addressing system is necessary in the selection process and factors such as associative lexical indices and rhythm (see Brown and McNeill, 1966, and Laver, 1970) obviously play an important role. Laver (1970) describes how we make conscious use of the addressing indices when we try to recall a forgotten word or phrase. Often we can remember only the stress pattern or syllabic structure of the forgotten item and we can use these as associative stimuli.

The formulation of the neurolinguistic programme at the grammatical level may involve similar procedures to those at the lexical level. One can postulate a sort of syntactical storage system containing grammatical rules of the language, and a monitoring system assessing the suitability of a selected grammatical construction for the expression of the original idea. There is obviously a close relationship between the selection of the grammatical construction and the lexical and phonological items in the planning process.

We can be a little more concrete about the phonological programme and its myodynamic execution. There must, once again, be some sort of storage system of phonological units which can be selected for the planning stage. As Ladefoged (1967a : 169) says, "there must be some stored units: all conceivable utterances cannot be stored as indivisible units in the context so that they are available should there be an occasion for their use." The favoured candidates for the minimal phonological unit in the neurolinguistic programme are the phoneme and the syllable. To support the claim that speech is ordered in terms of invariant phoneme "commands" to the articulatory muscles, various researchers have used electromyographic evidence from oral structures such as the lips and palate (e.g. Harris, Lysaught and Schvey 1965). The EMG readings supposedly demonstrated the considerable degree of constancy in the motor commands issued to the muscles which accompany any given phoneme. (Liberman, Cooper, Shankweiler and Studdert-Kennedy, 1967). It is well known, however, that the acoustic and articulatory correlates of any given phoneme vary according to the context in which it appears. The authors of phoneme-based models would consider this peripheral variability to be due to factors such as mechanical constraints inherent in the peripheral vocal structures, and overlapping in time with the effects of successive phoneme commands (MacNeilage, 1970).

There is some doubt as to the reliability of interpreting EMG readings from rapidly contracting muscles such as those used in speech articulations (see Chapter 3, section 1.3.1.). Indeed, some subsequent EMG studies of labial articulation (by Fromkin, 1968; and by Tathan and Morton, 1968) have suggested EMG readings associated with particular phonemes are different according to context.

Fromkin (1968) offers evidence to suggest that EMG readings for [p] and [b] differ according to whether they are in initial or final position in the syllable, although she did find evidence of invariant neural commands for the phonemes in either of the two positions. She used this evidence to suggest that speech may be organised in terms of the syllable, rather than the phoneme as the basic neural unit. The motor commands to phonemes would then be regarded as having neural invariance only in terms of their organisation within the syllable.

Rather than trying to posit neural invariances corresponding to particular linguistic categories such as phoneme or syllable, MacNeilage (1970) proposes what might be called "a target theory of speech production." The basic idea of this theory is that "speech is controlled, in part, by the specification of targets in an internalised space co-ordinate system." (MacNeilage 1970 : 189). A major point in this theory is that the control of speech is analogous to that of other human activities and that concepts taken from theories of general behaviour are applicable to speech. One of these concepts is the theory of "motor equivalence" which accounts for "a variability of specific muscular responses with circumstance in such a way as to produce a single result" (Hebb, 1949 : 153, cited by MacNeilage 1970). Thus a certain end result or target (such as opening a door or making a particular articulation) remains the same but the detailed motor behaviour involved in reaching the goal can be quite variable (MacNeilage 1970 : 186). If speech production is planned in terms of targets there is no need to postulate a large store of fixed motor command patterns for each allophone of a phoneme. It is necessary, however, to show how the achievement of targets during speech is controlled. The above-mentioned feedback system is one way in which this control may be provided.

1.2. The Motor Execution System

So far in this Chapter we have discussed some aspects of the formulation of the neurolinguistic programme. It is now proposed to speculate on how the articulatory programme is executed and controlled during speech production. Attention will be focussed primarily on the control of the upper articulators particularly of the tongue and mandible, although most of what we have to say will apply also to the other speech organs.

As mentioned earlier, there are certain constraints imposed on the motor execution of the programme at the periphery, which must be taken into account in any adequate model of speech production. These constraints arise from the transmission of motor impulses and the mechanics of muscular contractions. It was seen in Chapter 2, how the rate of the transmission of the neural impulse varied according to such biological factors as the diameter of the axon, composition of the myelin sheath etc. Also the time taken for a neural impulse to reach the muscle is related to the length of the nerve fibre. This has interesting implications for the temporal co-ordination of such muscular systems as those of the tongue and the larynx where the lengths of the motor nerves supplying these organs are different. As Lenneberg (1967) says, "the anatomy of the nerves suggests that innervation time for intrinsic laryngeal muscles may easily be up to 30 msec. longer than innervation time for muscles in and around the oral cavity. Considering now that some articulatory events may last as short a period as 20 msec., it becomes a reasonable assumption that the firing order in the brain stem may at times be different from the order of events occurring at the periphery..." (p. 96). Although Lenneberg's ideas are interesting, one cannot place too much reliance on his methods of arriving at the figure of 30 msec. Short of actually isolating a particular nerve fibre in a living person and measuring the time taken for an impulse to be transmitted along its length, the figure mentioned by Lenneberg must remain speculative. Besides, this difference in time would only be relevant if the two motor fibres measured were exactly similar in diameter, sheath composition etc. This is extremely difficult to ascertain in a typical cranial mixed nerve which consists of a very large number of sensory and motor fibres of different diameters. However, Lenneberg's hypothesis is an interesting one and should certainly stimulate further research.

Other constraints on the motor execution system arise from the mechanics of muscular contraction. As we saw in Chapter 2, section 2. 3. 1., the degree of force developed by a muscle and the time taken to achieve this force in tetanic contraction will depend on a number of factors including the elasticity and other mechanical properties of the muscle such as its mass and inertia, the number of motor units active at any one time, the frequency of successive activations within motor units and the mechanical properties of the imposed load. Because of these constraints, the relationship between the motor plan of the target articulation and such motor commands as are sent to the musculature through the efferent nerves is very complex and nonunivocal. There must be some element in the speech system which can make necessary compensations for these muscular constraints to control the precisely timed articulatory movements. Bernstein (1967), in discussing the lack of one-to-one correspondence between motor commands and actions produced at various junctures says, "It is clear that organisms, whose only channels of operation upon the surrounding world are commands given to their muscles, may achieve controlled movements serving a particular purpose only by means of continuous monitoring and control achieved by the participation of the sense organs". (p. 146).

1. 3. Aspects of Feedback Control of Speech

The control of speech is probably made possible by means of a closed-loop or feedback system. Such a system fulfills the monitoring function mentioned earlier in this section and consists of the following basic processes: an input consisting of motor commands to the articulatory muscles, feedback of afferent information from the sensory resources in the oral structures, comparison of the feedback information with an idealised target plan, and regulation of the motor commands according to this feedback information. We shall examine some of the more important aspects of this control system.

As we saw in Chapter 2 and in the early sections of the previous

Chapter, the three main feedback channels, the tactile, proprioceptive and auditory, can provide the C. N. S. with detailed sensory information concerning many aspects regarding the present state of the peripheral articulatory organs: tactile feedback, from the free-endings and complex organised receptors conveys information concerning such factors as the precise location, the pressure, and timing of contacts between articulatory structures; proprioceptive feedback, from muscle spindles, tendon organs and joint receptors conveys information such as the length of the muscles, the amount of force exerted by the muscles, the rate of change of muscle length, and the velocity of stretch in the muscles; auditory feedback, from complex receptors in the ear conveys information about acoustic characteristics of the resulting articulatory movements. (As seen in Fig. 42, the acoustic feedback is conducted via two channels representing the acoustic pathways to the ear through the air and through the body tissues). One important function of the feedback of all this detailed sensory information is that it enables the C. N. S. to build up a complex and quite detailed internal space co-ordinate system of the oral tract. Lashley (1951) recognised the importance of an internalised spatial representation of the axes of the body during the maintenance of posture: "This postural system is based on excitations from proprioceptors. The distance receptors impose an additional set of space co-ordinates upon the postural system, which in turn continually modifies the co-ordinates of the distance receptors. The dropped cat rights itself, if either the eyes or the vestibular senses are intact, but not in the absence of both." (Lashley 1951 : 190). It is plausible that such a space co-ordinate system exists for the vocal tract and serves as a sort of blueprint on which targets are plotted during the planning stage of an articulation. Because of the close association between motor activity and sensory information contributing to this internalised representation, any target plan will necessarily also incorporate an appropriate sensory schema of the vocal organs. This means that both motor and sensory correlates of the target articulation are "primed" or "pre-set" before the actual performance of the articulation. This "priming in advance" notion has been used as a possible explanation for the "overshoot" effect in the experiment described in Chapter 6 (section 2.4.).

Closely related to their functions in providing a detailed space co-ordinate system of the vocal tract is the role played by the feedback mechanisms in on-going control of articulation. The feedback channels are here used to provide a continuous running "plot" of the situation that actually obtains at the periphery to be compared with the idealised target positions. This comparing process takes place in the brain probably at the level of the cerebellum. It perhaps works as follows: Information concerning the idealised target articulation (I), i.e. the intended position of the vocal organs, is fed into a comparator unit (see Fig. 42), together with sensory feedback from the periphery indicating the actual position the vocal organs are adopting at any given time, (A). The difference between the intended goal I, and the actual position reached by the articulators A, is calculated by the comparator in terms of what is usually called an error signal (see Fairbanks, 1954). Thus at any given time, the error signal gives a measure of the amount by which the target articulation has not yet been reached by the speech organs. If the error signal equals zero then the goal I will equal A and the next element of the programme, (presumably the next target) is "triggered off" and proceeds to the motor execution stage. If, however, as is usually the case, the error signal does not equal zero it provides data which enables the motor commands to the muscles to be adjusted so as to bring the error signal closer to zero. This adjustment probably takes place in some sort of regulator unit into which both the error signal and the motor schema of the target are fed. The motor commands to the muscles are modified, causing the output, relayed back to the comparator in the form of feedback signals, more nearly to equal the target plan, and thus reduce the error signal, (see Fairbanks, 1954). This closed-loop process continues until the motor commands are modified so that the output equals the intended target. It is probable, however, that the output will not always exactly equal the intended target. Presumably, a certain amount of error signal is permitted before any correctional activities take place.

The results of the experiment described in Chapter 6 enable us to make certain hypotheses concerning the nature of the error signal and the process of regulating the motor commands. In the interpretation of the results, it was suggested that the error signal will be relatively large when normal sensory feedback is diminished either by anaesthetic (particularly lingual block) or masking noise. This may be because the required amount of sensory information appropriate to the target was not sent back via the different channels. In attempting to reduce the error signal during an articulation, the regulator may try certain procedures such as attempting to increase the area of contact between the tongue and palate (so increasing the amount of sensory information) either by increasing the firing rate of motor impulses to the same tongue muscles or by sending commands to other muscles, so that a greater area of contact is achieved. Both these procedures may involve increased duration of the articulation (see results Chapter 6, section 3.4.1.2.). There is clear evidence from the electropalatographic data that the movement of the tongue is modified in certain predictable ways under the sensory alteration conditions, so the motor commands to produce these movements must have been altered accordingly.

Any closed-loop system such as the one proposed here for the control of speech production involves a certain amount of time for the neural impulses to travel round the feedback circuit. Lashley (1951) has suggested that, because of this time-lag, it would not be possible for such a system to control fast, accurate movements: "Whip-snapping movements of the hand can be regulated accurately in extent, yet the entire movement, from initiation to completion, requires less than the reaction time for tactile or kinesthetic stimulation of the arm, which is about one-eighth of a second..." (p. 188). For this reason, Lashley postulates that an effector mechanism can be "pre-set" or "primed" to discharge at a given intensity or for a given duration, independent or any sensory controls. However, he gives no indication as to how he arrived at the figure of one-eighth of a second. It seems pretty clear now that some feedback mechanisms, e.g. afferent discharge from primary endings of muscle spindles, can operate with latencies very much shorter than one-eighth of a second. Kugelberg (1952) and Rushworth (1966) (both quoted by Ohala, 1970) have shown the existence of facial reflexes in humans such as the eyeblink, which have extremely short latencies of the order of 12-15 msec. or less. It is possible that monosynaptic reflex arcs such as those involved in the hypothesised gamma-loop control (see Chapter 2, section 1.2.2.) of the tongue, could have similar short delays. It would seem also that, because of the shorter distances involved, the feedback of afferent information and subsequent motor commands via the large fibre in the cranial nerves (i.e. those supplying the primary endings of muscle spindles and cutaneous tactile receptors), would be considerably faster than would be the case with reflex arcs associated with fast movements of the hand.

However, even assuming there were no feedback mechanisms fast enough to provide on-going control, it is not necessary that the target articulation be completed before afferent information is sent back to the planning unit. In fact, it seems plausible that the control system can extrapolate into the future, and so predict the position that the articulatory organs will attain, after a specific interval of time. We have seen, earlier, how the muscle spindle is capable of providing "predictive" information about the behaviour of a muscle (see Chapter 2, section 1.2.2. and 1.3.2.), thus allowing compensation in advance by the regulator system. Consequently, it may not be necessary for each stage of the planning function to wait until the error signal of the previous stage equals zero. As Fairbanks (1954 : 137) says:
"The advancement of the storage component to the next control point is not necessarily delayed until the actual moment when a condition of zero error signal obtains. It can be triggered in advance of that time by an amount, let us say, equal to the relevant time constants. By this means, over suitable channels, a new input can be started on its way towards the effector before the previous control point has been reached, so that it will arrive there at an appropriate anticipated time."

So far, we have been discussing on-going closed-loop control during articulation <u>after</u> the initial reception of feedback information by the comparator. What happens however, when the model starts operating from an inactive state, i.e. when the motor commands are as yet unmodified by the effect of the error signal. It seems plausible that in the initial stage of the utterance, commands are issued to relevant articulatory organs via the gamma efferent fibres (see Chapter 2, section 1.2.2.). These will ensure at the outset that the articulators achieve the prescribed positions, irrespective of local conditions at the periphery. After these initial motor commands have been issued, the sensory feedback control takes over. There is some experimental evidence to suggest that some sort of control is operative during the initiation of an utterance. MacNeilage, Krones and Hanson (1969) have shown in a recent study of jaw movements, that the jaw adopts a consistent position for articulation of a given segment,even though the pre-speech positions of the jaw vary considerably.

In this Chapter so far,we have discussed some aspects of a speaker's production and control of articulation. Some preliminary hypotheses have been offered about how the actual situation and the desired target can be specified on an internal space co-ordinate system and together may lead to the generation of appropriate motor commands. Presumably, an analogous situation exists with an independent listener. He receives auditory information which can be plotted on his own internal co-ordinate system and thereby obtains a specification of the speaker's target articulation.

CHAPTER 8

GENERAL CONCLUSIONS

In the Introduction to this thesis we discussed the close relationship that has always existed between theoretical interests in experimental phonetics and available instrumental technology. It seems at the present time, with research interests focussed primarily on articulatory aspects of speech production, that instrumental techniques will continue to play an essential role in providing detailed quantitative and qualitative information concerning many different aspects of the speech output, particularly the dynamics of articulation. We have seen in this thesis how one of the more recent instrumental techniques, electropalatography, was developed as an analytic technique to provide some of this vital information. The feasability of the technique as a research tool was clearly demonstrated in the experiment described in Chapter 6, where it provided details of the exact location and timing of tongue contacts with the palate under different experimental conditions. Using electropalatography, it was possible in this experiment to determine relatively slight changes in tongue configuration, e.g. changes in the width of the central groove in the tongue during articulation of the fricatives [s] and [ʃ]. Although in its present form electropalatography has been demonstrably valuable as an analytic research technique, some refinements are necessary before it becomes maximally useful in providing detailed spatio-temporal data. It will need to incorporate more electrodes in the artificial palate so providing more accurate details of the location of tongue-palate contacts. Also some more suitable method of processing the data will be necessary before any large scale investigations can be carried out. This problem will hopefully be solved in the near future by a computer link-up system.

Electropalatography provides data on aspects of the articulatory activity of one organ only. For it to be of maximum benefit to research, it will probably be used in conjunction with other instrumental techniques such as electromyography and cinefluorography. Modifications are needed also to these latter techniques. Electromyography, which provides direct records of electrical activity associated with muscular contractions is a particularly valuable technique because it leads one straight into speculation about the co-ordination of neuro-muscular processes involved in speech. However, as was pointed out in Chapter 3, there are still a number of serious limitations associated with its use in recording from complex muscles such as those used in speech production. Hopefully, improved design of electrodes will soon make it possible to record electrical activity from individual motor units of complex interdigitating muscle systems, such as the intrinsic muscles of the tongue. Cinefluorography is also an extremely useful technique but radiation danger continues to be a severe limitation. However, here also, refinements are at present being made. Experiments with special image-intensifying systems involving pulsed microbeams with on-line computer control seem particularly promising. Hopefully we will soon be able to obtain simultaneous registration of the dynamics of articulatory structures such as the soft palate, tongue, mandible, thyroid, lips and lateral pharyngeal wall, in addition to measuring soft-tissue pressures, intra-oral air pressures, sub-glottal pressure and lung volume level. Records such as these will provide us with valuable data on the co-ordination and timing of the different articulatory structures used in speech production.

Instrumental investigations in phonetic research today are aimed primarily at making more precise, the descriptive articulatory theories of speech production. Such investigations, however, need to be accompanied by detailed anatomical and physiological frameworks, particularly so that one can be aware of the constraints imposed on articulation by biological systems. With improved articulatory descriptions of activities of the speech organs, together with detailed knowledge of their anatomy and physiology it is now possible to begin to formulate a more comprehensive peripheral and motor component of a linguistic performance theory. In this thesis, an attempt has been made to point to the direction such a theory should take, by outlining a parametric approach to a description of lingual articulation, by means of which one can specify not only all possible lingual motions and configurations, but also the underlying physiological mechanisms involved in producing the articulatory parameters. Some basic concepts of phonetic theory such as specification of vowels in terms of tongue height were rescrutinized in the light of this parametric approach. It was also seen how physiological characteristics of the articulatory organs such as the interaction of extrinsic and intrinsic muscle groups in the tongue can explain certain co-articulatory features.

It was mentioned above that the main interest in experimental phonetic research today is centred on the dynamics of articulation. The main reason for this emphasis on dynamic aspects of speech is that such data may provide peripheral evidence for neural programming functions and the co-ordination and regulation of articulatory movements. In Chapter 6 an experiment was described which involved the investigation, by instrumental techniques such as electropalatography and spectrography, of certain acoustic and articulatory aspects of speech production under different sensory feedback deprivation conditions. Electropalatography showed evidence of target missing, particularly in the articulation of fricatives [s] and [ʃ] and this generated some interesting hypotheses regarding the control of speech production. A closed-loop theory of the regulation and co-ordination of lingual articulation was proposed, in which sensory feedback was regarded as providing not only a detailed space co-ordinate system of the vocal tract, but also a continuous ongoing "plot" of the position and velocity of the articulatory organs, by means of which the CNS can monitor target articulations. We still need much more information about the brain's use of tactile, proprioceptive and auditory feedback systems. The experimental procedures of lingual block, topical anaesthesia and auditory masking that were used in this investigation, however, seem particularly promising techniques for providing much of this information, provided of course, they are adequately controlled and accompanied by a detailed anatomical and physiological framework.

The area covered in this thesis has necessarily been rather limited. Only one subject was used in the detailed electropalatography investigations, and interest was focussed primarily on lingual articulation. It is proposed to extend the range of this research by including electropalatographic data from many different speakers and from a wider range of articulations. The parametric articulatory approach outlined in Chapter 5 will also be extended to other articulatory structures such as the lips and mandible. We will then hopefully be well on the way to formulating a more comprehensive phonetic theory of linguistic performance.

APPENDIX I.

COMPUTER PRINT-OUTS OF THE RESULTS OF THE EXPERIMENT DESCRIBED IN CHAPTER 6.

Explanation of Some of the Symbols Used.

NORM	- Normal condition
T	- Topical anaesthetic condition
A	- Auditory masking condition
T-A	- Topical an. with auditory masking
LB	- Lingual block condition
LB-T	- Lingual block with topical an.
LB-A	- Lingual block with auditory masking
LTA	- Lingual block with both topical an. and auditory masking
STD	- Standard
S.E.	- Standard error
M	- Mean
V	- Variance
REP 1	- First replication of the experiment
REP 2	- Second replication of the experiment
MEANS	- Means for both replications

In the two-way tables NO-A refers to those conditions not involving A (hence NO-L, NO-T). The unlabelled means in the two-way tables are the terminal means, obtained by averaging the two adjacent figures.

MEANS, VARS, & STD ERRORS OF MEANS FOR VARIABLE FREQ S1 LOWER i.e. [s] in "see"

		NORM	T	A	T-A	LB	LB-T	LB-A	LT.A	MEANS
REP1	M.	3141.67	3200.00	3141.67	3250.00	3350.00	3383.33	3483.33	3483.33	3304.17
	V.	2422.40	8998.40	12422.40	11004.80	8000.00	6672.00	5667.20	19664.00	
	S.E.	(20.093)	(38.726)	(45.502)	(42.827)	(36.515)	(33.347)	(30.733)	(57.248)	
REP2		3200.00	3166.67	3158.33	3408.33	3358.33	3375.00	3416.67	3425.00	3313.54
		998.40	6665.60	10419.20	3420.80	1417.60	3756.80	8672.00	9750.40	
		(12.900)	(33.331)	(41.672)	(23.877)	(15.371)	(25.023)	(38.018)	(40.312)	
MEANS		3170.83	3183.33	3150.00	3329.17	3354.17	3379.17	3450.00	3454.17	3308.85
		1710.40	7832.00	11420.80	7212.80	4708.80	5214.40	7169.60	14707.20	
		(11.939)	(25.547)	(30.850)	(24.517)	(19.809)	(20.845)	(24.443)	(35.009)	

TWO-WAY TABLES OF MEANS

	NO-A	A	
NO-L	3177.08	3239.58	3208.33
L	3366.67	3452.08	3409.37
	3271.87	3345.83	3308.85

	NO-T	T	
NO-L	3160.42	3256.25	3208.33
L	3402.08	3416.67	3409.37
	3281.25	3336.46	3308.85

	NO-T	T	
NO-A	3262.50	3281.25	3271.87
A	3300.00	3391.67	3345.83
	3281.25	3336.46	3308.85

MEANS, VARS, & STD ERRORS OF MEANS FOR VARIABLE FREQ S2 LOWER   i.e. [s] in "saw"

	NORM	T	A	T-A	LB	LB-T	LB-A	LTA	MEANS
REP1 M	3025.00	3291.67	3166.67	3483.33	3266.67	3441.67	3341.67	3633.33	3331.25
V.	8755.20	20422.40	48665.60	28665.60	11667.20	1424.00	9417.60	43667.20	
S.E.	(38.199)	(58.342)	(90.061)	(69.120)	(44.097)	(15.406)	(39.618)	(85.310)	
REP2	3066.67	3291.67	3275.00	3441.67	3241.67	3366.67	3358.33	3483.33	3315.62
	5667.20	18422.40	46748.80	14425.60	10419.20	10668.80	5417.60	28665.60	
	(30.733)	(55.411)	(88.269)	(49.033)	(41.672)	(42.168)	(30.049)	(69.120)	
MEANS	3045.83	3291.67	3220.83	3462.50	3254.17	3404.17	3350.00	3558.33	3323.44
	7211.20	19422.40	47707.20	21545.59	11043.20	6046.40	7417.59	36166.39	
	(24.514)	(40.231)	(63.052)	(42.373)	(30.336)	(22.447)	(24.862)	(54.899)	

TWO-WAY TABLES OF MEANS

	NO-A	A	
NO-L	3168.75	3341.67	3255.21
L	3329.17	3454.17	3391.67
	3248.96	3397.92	3323.44

	NO-T	T	
NO-L	3133.33	3377.08	3255.21
L	3302.08	3481.25	3391.67
	3217.71	3429.17	3323.44

	NO-T	T	
NO-A	3150.00	3347.92	3248.96
A	3285.42	3510.42	3397.92
	3217.71	3429.17	3323.44

MEANS, VARS, & STD ERRORS CF MEANS FOR VARIABLE FREQ SS1 i.e. [ʃ] in "she"

		NORM	T	A	T-A	LB	LB-T	LB-A	LTA	MEANS
REP1	M	2291.67	2283.33	2266.67	2350.00	2416.67	2300.00	2316.67	2125.00	2293.75
	V.	2416.00	6665.60	7667.20	4998.40	9667.20	4998.40	12665.60	14748.80	
	S.E.	(20.067)	(33.331)	(35.747)	(28.863)	(40.140)	(28.863)	(45.945)	(49.580)	
REP2		2266.67	2258.33	2241.67	2266.67	2275.00	2275.00	2233.33	2258.33	2259.37
		5667.20	2416.00	7414.40	21667.20	1750.40	9750.40	9667.20	8416.00	
		(30.733)	(20.067)	(35.153)	(60.093)	(17.080)	(40.312)	(40.140)	(37.452)	
MEANS		2279.17	2270.83	2254.17	2308.33	2345.83	2287.50	2275.00	2191.67	2276.56
		4041.60	4540.80	7540.80	13332.80	5708.80	7374.40	11166.39	11582.40	
		(18.352)	(19.452)	(25.068)	(33.333)	(21.811)	(24.790)	(30.505)	(31.068)	

TWO-WAY TABLES CF MEANS

	NO-A	A	
NO-L	2275.00	2281.25	2278.12
L	2316.67	2233.33	2275.00
	2295.83	2257.29	2276.56

	NO-T	T	
NO-L	2266.67	2289.58	2278.12
L	2310.42	2239.58	2275.00
	2288.54	2264.58	2276.56

	NO-T	T	
NO-A	2312.50	2279.17	2295.83
A	2264.58	2250.00	2257.29
	2288.54	2264.58	2276.56

MEANS, VARS, & STD ERRORS OF MEANS FOR VARIABLE FREQ SS2 i.e. [ʃ] in "Shaw"

		NORM	T	A	T-A	LB	LB-T	LB-A	LTA	MEANS
REP1	M	2316.67	2275.00	2233.33	2325.00	2225.00	2275.00	2366.67	2325.00	2292.71
	V.	8665.60	12748.80	1667.20	6748.80	25750.40	5750.40	2668.80	8748.80	
	S.E.	(38.003)	(46.096)	(16.669)	(33.538)	(65.511)	(30.958)	(21.090)	(38.186)	
REP2		2250.00	2183.33	2158.33	2350.00	2233.33	2108.33	2191.67	2316.67	2223.96
		10000.00	22665.60	3414.40	12000.00	6668.80	1414.40	9414.40	5667.20	
		(40.825)	(61.462)	(23.855)	(44.721)	(33.339)	(15.354)	(39.611)	(30.733)	
MEANS		2283.33	2229.17	2195.83	2337.50	2229.17	2191.67	2279.17	2320.83	2258.33
		9332.80	17707.20	2540.80	9374.40	16209.60	3582.40	6041.60	7208.00	
		(27.888)	(38.414)	(14.551)	(27.950)	(36.753)	(17.278)	(22.438)	(24.508)	

TWO-WAY TABLES OF MEANS

	NO-A	A	
NO-L	2256.25	2266.67	2261.46
L	2210.42	2300.00	2255.21
	2233.33	2283.33	2258.33

	NO-T	T	
NO-L	2239.58	2283.33	2261.46
L	2254.17	2256.25	2255.21
	2246.87	2269.79	2258.33

	NO-T	T	
NO-A	2256.25	2210.42	2233.33
A	2237.50	2329.17	2283.33
	2246.87	2269.79	2258.33

MEANS, VARS, & STD ERRORS CF MEANS FOR VARIABLE FORMANT1SSI i.e. [i] in "she"

		NORM	T	A	T-A	LB	LB-T	LB-A	LTA	MEANS
REP1	M.	360.00	381.67	371.67	411.67	421.67	377.50	350.00	358.33	379.06
	V.	280.00	86.67	446.67	376.67	856.80	617.50	250.00	256.67	
	S.E.	(6.331)	(3.801)	(8.628)	(7.923)	(11.950)	(10.145)	(6.455)	(6.541)	
REP2		466.67	457.50	452.50	441.67	401.67	384.17	450.00	375.00	428.65
		666.80	1137.60	137.60	1386.80	266.67	364.17	40.00	1390.00	
		(10.542)	(13.770)	(4.789)	(15.203)	(6.667)	(7.791)	(2.582)	(15.221)	
MEANS		413.33	419.58	412.08	426.67	411.67	380.83	400.00	366.67	403.85
		473.40	612.14	292.14	881.74	561.74	490.84	145.00	823.34	
		(6.281)	(7.142)	(4.934)	(8.572)	(6.842)	(6.396)	(3.476)	(8.283)	

TWO-WAY TABLES CF MEANS

	NO-A	A	
NO-L	416.46	419.37	417.92
L	396.25	383.33	389.79
	406.35	401.35	403.85

	NO-T	T	
NO-L	412.71	423.12	417.92
L	405.83	373.75	389.79
	409.27	398.44	403.85

	NO-T	T	
NO-A	412.50	400.21	406.35
A	406.04	396.67	401.35
	409.27	398.44	403.85

MEANS, VARS, & STD ERRORS OF MEANS FOR VARIABLE FORMANT2 SSI i.e. [i] in "she"

	NORM	T	A	T-A	LB	LB-T	LB-A	LTA	MEANS
REP1 M.	1990.83	1985.00	1970.83	1918.33	1962.50	1981.67	1918.33	1890.00	1952.19
V.	665.60	140.80	601.60	1366.40	480.00	1619.20	39814.40	953.60	
S.E.	(10.532)	(4.844)	(10.013)	(15.091)	(8.944)	(16.428)	(81.460)	(12.607)	
REP2	2045.83	2015.83	1951.66	1935.00	2068.33	2015.83	1991.67	1929.17	1994.17
	1104.00	1206.40	2384.00	2000.00	1456.00	368.00	1664.00	3603.20	
	(13.565)	(14.180)	(19.933)	(18.257)	(15.578)	(7.832)	(16.653)	(24.506)	
MEANS	2018.33	2000.42	1961.25	1926.67	2015.42	1998.75	1955.00	1909.58	1973.18
	884.80	673.60	1492.80	1683.20	968.00	993.60	20739.20	2278.40	
	(8.587)	(7.492)	(11.153)	(11.843)	(8.981)	(9.099)	(41.572)	(13.779)	

TWO-WAY TABLES OF MEANS

	NO-A	A	
NO-L	2009.37	1943.96	1976.67
L	2007.08	1932.29	1969.69
	2008.23	1938.12	1973.18

	NO-T	T	
NO-L	1989.79	1963.54	1976.67
L	1985.21	1954.17	1969.69
	1987.50	1958.85	1973.18

	NO-T	T	
NO-A	2016.87	1999.58	2008.23
A	1958.12	1918.12	1938.12
	1987.50	1958.85	1973.18

MEANS, VARS, & STD ERRORS OF MEANS FOR VARIABLE:FORMANT1 SI i.e. [i] in "see"

		NORM	T	A	T-A	LB	LB-T	LB-A	LTA	MEANS
REP1	M.	367.50	399.17	398.33	405.00	409.17	392.50	340.83	370.00	385.31
	V.	437.50	204.17	1066.67	300.00	524.17	177.50	624.17	1850.00	
	S.E.	(8.539)	(5.833)	(13.333)	(7.071)	(9.347)	(5.439)	(10.199)	(17.559)	
REP2		445.83	417.50	462.50	445.00	384.17	393.33	454.17	412.50	426.87
		354.20	277.50	437.60	670.00	654.17	26.67	354.20	437.50	
		(7.683)	(6.801)	(8.540)	(10.567)	(10.442)	(2.109)	(7.683)	(8.539)	
MEANS		406.67	408.33	430.42	425.00	396.67	392.92	397.50	391.25	406.09
		395.85	240.84	752.14	485.00	589.17	102.09	489.19	1143.75	
		(5.743)	(4.480)	(7.917)	(6.357)	(7.007)	(2.917)	(6.385)	(9.763)	

TWO-WAY TABLES OF MEANS

	NO-A	A	
NO-L	407.50	427.71	417.60
L	394.79	394.37	394.58
	401.15	411.04	406.09

	NO-T	T	
NO-L	418.54	416.67	417.60
L	397.08	392.08	394.58
	407.81	404.37	406.09

	NO-T	T	
NO-A	401.67	400.62	401.15
A	413.96	408.13	411.04
	407.81	404.37	406.09

MEANS, VARS, & STD ERRORS OF MEANS FOR VARIABLE FORMANT2 SI i.e. [i] in "see"

	NORM	T	A	T-A	LB	LB-T	LB-A	LTA	MEANS
REP1 M.	1971.67	1953.33	1906.67	1896.67	1964.17	1950.00	1901.67	1860.00	1925.52
V.	867.20	112.00	1548.80	1068.80	745.60	2249.60	2816.00	649.60	
S.E.	(12.022)	(4.320)	(16.067)	(13.347)	(11.147)	(19.363)	(21.664)	(10.405)	
REP2	1998.33	1948.33	1890.00	1854.17	2039.17	2000.00	1932.50	1920.83	1947.92
	867.20	860.80	1603.20	1100.80	1305.60	841.60	652.80	4601.60	
	(12.022)	(11.978)	(16.346)	(13.545)	(14.751)	(11.843)	(10.431)	(27.694)	
MEANS	1985.00	1950.83	1898.33	1875.42	2001.67	1975.00	1917.08	1890.42	1936.72
	867.20	486.40	1576.00	1084.80	1025.60	1545.60	1734.40	2625.60	
	(8.501)	(6.367)	(11.460)	(9.508)	(9.245)	(11.349)	(12.022)	(14.792)	

TWO-WAY TABLES OF MEANS

	NO-A	A	
NO-L	1967.92	1886.87	1927.39
L	1988.33	1903.75	1946.04
	1978.12	1895.31	1936.72

	NO-T	T	
NO-L	1941.67	1913.12	1927.39
L	1959.37	1932.71	1946.04
	1950.52	1922.92	1936.72

	NO-T	T	
NO-A	1993.33	1962.92	1978.12
A	1907.71	1882.92	1895.31
	1950.52	1922.92	1936.72

MEANS, VARS, & STD ERRORS OF MEANS FOR VARIABLE FORMANT1 SSO i.e. [ɔ] in "Shaw"

		NORM	T	A	T-A	LB	LB-T	LB-A	LTA	MEANS
REP1	M.	454.17	463.33	465.00	464.17	453.33	433.33	426.67	439.17	449.90
	V.	1354.20	346.80	180.00	404.20	26.80	916.80	1716.80	304.20	
	S.E	(15.023)	(7.603)	(5.477)	(8.208)	(2.113)	(12.361)	(16.915)	(7.120)	
REP2		495.83	485.00	505.83	491.67	464.17	464.17	493.33	479.17	484.90
		104.20	590.00	104.20	256.80	154.20	654.20	146.80	444.20	
		(4.167)	(9.916)	(4.167)	(6.542)	(5.070)	(10.442)	(4.946)	(8.604)	
MEANS		475.00	474.17	485.42	477.92	458.75	448.75	460.00	459.17	467.40
		729.20	468.40	142.10	330.50	90.50	785.50	931.80	374.20	
		(7.795)	(6.248)	(3.441)	(5.248)	(2.746)	(8.091)	(8.812)	(5.584)	

TWO-WAY TABLES OF MEANS

	NO-A	A	
NO-L	474.58	481.67	478.12
L	453.75	459.58	456.67
	464.17	470.62	467.40

	NO-T	T	
NO-L	480.21	476.04	478.12
L	459.37	453.96	456.67
	469.79	465.00	467.40

	NO-T	T	
NO-A	466.87	461.46	464.17
A	472.71	468.54	470.62
	469.79	465.00	467.40

MEANS, VARS, & STD ERRORS OF MEANS FOR VARIABLE FORMANT2 SSO i.e. [ɔ] in "Shaw"

		NORM	T	A	T-A	LB	LB-T	LB-A	LTA	MEANS
REP1	M.	830.00	825.83	861.67	880.00	810.83	803.33	855.83	816.67	835.52
	V.	190.00	294.60	1176.80	760.00	424.20	276.80	604.20	386.80	
	S.E.	(5.627)	(7.007)	(14.005)	(11.255)	(8.408)	(6.792)	(10.035)	(8.029)	
REP2		821.67	824.17	871.67	875.00	809.17	796.67	830.83	815.83	830.62
		306.80	1464.20	296.80	1000.20	714.20	806.80	344.20	904.20	
		(7.151)	(15.622)	(7.033)	(12.911)	(10.910)	(11.596)	(7.574)	(12.276)	
MEANS		825.83	825.00	866.67	877.50	810.00	800.00	843.33	816.25	833.07
		248.40	879.40	736.80	880.10	569.20	541.80	474.20	645.50	
		(4.550)	(8.561)	(7.836)	(8.564)	(6.887)	(6.719)	(6.286)	(7.334)	

TWO-WAY TABLES OF MEANS

	NO-A	A	
NO-L	825.42	872.08	848.75
L	805.00	829.79	817.40
	815.21	850.94	833.07

	NO-T	T	
NO-L	846.25	851.25	848.75
L	826.67	808.12	817.40
	836.46	829.69	833.07

	NO-T	T	
NO-A	817.92	812.50	815.21
A	855.00	846.87	850.94
	836.46	829.69	833.07

MEANS, VARS, & STD ERRORS CF MEANS FOR VARIABLE FORMANT1 SO i.e. [ɔ] in "saw"

	NORM	T	A	T-A	LB	LB-T	LB-A	LTA	MEANS
REP1 M.	468.33	461.67	495.83	451.67	460.00	430.83	492.50	487.50	468.54
V.	366.80	126.80	354.20	1816.80	120.00	254.20	1637.60	187.60	
S.E.	(7.819)	(4.597)	(7.683)	(17.401)	(4.472)	(6.509)	(16.521)	(5.592)	
REP2	475.00	485.00	522.50	505.83	465.00	475.83	505.83	513.33	493.54
	250.00	300.00	167.60	354.20	180.00	74.20	104.20	376.80	
	(6.455)	(7.071)	(5.285)	(7.683)	(5.477)	(3.517)	(4.167)	(7.925)	
MEANS	471.67	473.33	509.17	478.75	462.50	453.33	499.17	500.42	481.04
	308.40	213.40	260.90	1085.50	150.00	164.20	870.90	282.20	
	(5.070)	(4.217)	(4.663)	(9.511)	(3.536)	(3.699)	(8.519)	(4.849)	

TWO-WAY TABLES CF MEANS

	NO-A	A	
NO-L	472.50	493.96	483.23
L	457.92	499.79	478.85
	465.21	496.87	481.04

	NO-T	T	
NO-L	490.42	476.04	483.23
L	480.83	476.87	478.85
	485.62	476.46	481.04

	NC-T	T	
NO-A	467.08	463.33	465.21
A	504.17	489.58	496.87
	485.62	476.46	481.04

MEANS, VARS, & STD ERRORS CF MEANS FOR VARIABLE FORMANT2 SO i.e. [ɔ] in "saw"

		NORM	T	A	T-A	LB	LB-T	LB-A	LTA	MEANS
REP1	M.	810.00	801.67	838.33	819.17	802.50	791.67	846.67	831.67	817.71
	V.	70.00	56.80	126.80	504.60	177.60	456.80	1106.80	366.80	
	S.E.	(3.416)	(3.077)	(4.597)	(9.171)	(5.441)	(8.725)	(13.582)	(7.819)	
REP2		808.33	815.00	841.67	822.50	775.83	780.83	816.67	805.00	808.23
		356.80	160.20	296.80	167.60	254.20	664.60	56.80	340.20	
		(7.711)	(5.167)	(7.033)	(5.285)	(6.509)	(10.525)	(3.077)	(7.530)	
MEANS		809.17	808.33	840.00	820.83	789.17	786.25	831.67	818.33	812.97
		213.40	108.50	211.80	336.10	215.90	560.70	581.80	353.50	
		(4.217)	(3.007)	(4.201)	(5.292)	(4.242)	(6.836)	(6.963)	(5.428)	

TWO-WAY TABLES CF MEANS

	NO-A	A	
NO-L	808.75	830.42	819.58
L	787.71	825.00	806.35
	798.23	827.71	812.97

	NO-T	T	
NO-L	824.58	814.58	819.58
L	810.42	802.29	806.35
	817.50	808.44	812.97

	NC-T	T	
NO-A	799.17	797.29	798.23
A	835.83	819.58	827.71
	817.50	808.44	812.97

MEANS, VARS, & STD ERRORS CF MEANS FOR VARIABLE FORMANT1 [I]

		NORM	T	A	T-A	LB	LB-T	LB-A	LTA	MEANS
REP1	M.	364.17	402.50	410.83	388.33	415.00	403.33	398.33	372.50	394.37
	V.	654.17	217.50	354.17	416.67	390.00	826.67	1066.67	2237.50	
	S.E.	(10.442)	(6.021)	(7.683)	(8.333)	(8.062)	(11.738)	(13.333)	(19.311)	
REP2		437.50	418.33	448.33	427.50	418.33	390.00	439.17	397.50	422.08
		437.60	1736.80	306.80	377.60	616.80	550.00	254.20	437.50	
		(8.540)	(17.014)	(7.151)	(7.933)	(10.139)	(9.574)	(6.509)	(8.539)	
MEANS		400.83	410.42	429.58	407.92	416.67	396.67	418.75	385.00	408.23
		545.89	977.15	330.49	397.14	503.40	688.34	660.44	1337.50	
		(6.745)	(9.024)	(5.248)	(5.753)	(6.477)	(7.574)	(7.419)	(10.557)	

TWO-WAY TABLES CF MEANS

	NO-A	A	
NO-L	405.62	418.75	412.19
L	406.67	401.87	404.27
	406.15	410.31	408.23

	NO-T	T	
NO-L	415.21	409.17	412.19
L	417.71	390.83	404.27
	416.46	400.00	408.23

	NC-T	T	
NO-A	408.75	403.54	406.15
A	424.17	396.46	410.31
	416.46	400.00	408.23

MEANS, VARS, & STD ERRORS CF MEANS FOR VARIABLE FORMANT2 [I]

		NORM	T	A	T-A	LB	LB-T	LB-A	LTA	MEANS
REP1	M.	1960.00	1958.33	1766.67	1728.33	1901.67	1920.83	1844.17	1763.33	1855.42
	V.	150.40	137.60	1417.60	1468.80	819.20	601.60	105.60	4432.00	
	S.E.	(5.007)	(4.789)	(15.371)	(15.646)	(11.685)	(10.013)	(4.195)	(27.178)	
REP2		1980.83	1930.83	1779.17	1750.00	2000.83	1900.00	1864.17	1841.67	1880.94
		348.80	1004.80	848.00	249.60	1456.00	748.80	905.60	2166.40	
		(7.625)	(12.941)	(11.888)	(6.450)	(15.578)	(11.171)	(12.285)	(19.002)	
MEANS		1970.42	1944.58	1772.92	1739.17	1951.25	1910.42	1854.17	1802.50	1868.18
		249.60	571.20	1132.80	859.20	1137.60	675.20	505.60	3299.20	
		(4.561)	(6.899)	(9.716)	(8.462)	(9.737)	(7.501)	(6.491)	(16.581)	

TWO-WAY TABLES CF MEANS

	NO-A	A	
NO-L	1957.50	1756.04	1856.77
L	1930.83	1828.33	1879.58
	1944.17	1792.19	1868.18

	NO-T	T	
NO-L	1871.67	1841.87	1856.77
L	1902.71	1856.46	1879.58
	1887.19	1849.17	1868.18

	NO-T	T	
NO-A	1960.83	1927.50	1944.17
A	1813.54	1770.83	1792.19
	1887.19	1849.17	1868.18

MEANS, VARS, & STD ERRORS OF MEANS FOR VARIABLE DUR SS1 i.e. [ʃ] in "she"

		NORM	T	A	T-A	LB	LB-T	LB-A	LTA	MEANS
REP1	M	16.28	15.45	20.81	21.26	19.79	18.32	25.21	23.64	20.09
	V	0.63	2.33	2.80	11.25	7.90	7.07	11.64	21.51	
	S.E.	(0.324)	(0.623)	(0.683)	(1.369)	(1.148)	(1.085)	(1.393)	(1.894)	
REP2		16.41	17.17	22.66	20.87	17.36	21.51	20.04	23.36	19.92
		0.67	1.67	4.43	1.28	2.21	8.06	8.96	4.87	
		(0.334)	(0.527)	(0.859)	(0.461)	(0.607)	(1.159)	(1.222)	(0.901)	
MEANS		16.34	16.31	21.74	21.06	18.58	19.92	22.63	23.50	20.01
		0.65	2.00	3.61	6.26	5.06	7.56	10.30	13.19	
		(0.233)	(0.408)	(0.549)	(0.722)	(0.649)	(0.794)	(0.926)	(1.048)	

TWO-WAY TABLES OF MEANS

	NO-A	A	
NO-L	16.33	21.40	18.86
L	19.25	23.07	21.16
	17.79	22.23	20.01

	NO-T	T	
NO-L	19.04	18.69	18.86
L	20.60	21.71	21.16
	19.82	20.20	20.01

	NO-T	T	
NO-A	17.46	18.11	17.79
A	22.18	22.28	22.23
	19.82	20.20	20.01

MEANS, VARS, & STD ERRORS CF MEANS FOR VARIABLE DUR VSSI i.e. [i] in "she"

		NORM	T	A	T-A	LB	LB-T	LB-A	LTA	MEANS
REP1	M.	15.70	18.45	20.04	21.19	18.19	18.00	21.77	22.79	19.52
	V.	1.58	1.08	9.43	2.39	1.75	3.52	3.72	17.24	
	S.E.	(0.514)	(0.424)	(1.253)	(0.631)	(0.539)	(0.766)	(0.788)	(1.695)	
REP2		15.83	18.77	22.28	22.72	17.11	19.41	22.15	20.75	19.88
		1.15	1.70	1.02	3.62	2.86	2.50	7.83	4.84	
		(0.439)	(0.533)	(0.413)	(0.777)	(0.690)	(0.646)	(1.142)	(0.898)	
MEANS		15.77	18.61	21.16	21.96	17.65	18.70	21.96	21.77	19.70
		1.37	1.39	5.22	3.00	2.30	3.01	5.77	11.04	
		(0.338)	(0.340)	(0.660)	(0.500)	(0.438)	(0.501)	(0.694)	(0.959)	

TWO-WAY TABLES CF MEANS

	NO-A	A	
NO-L	17.19	21.56	19.37
L	18.18	21.86	20.02
	17.68	21.71	19.70

	NO-T	T	
NO-L	18.46	20.28	19.37
L	19.80	20.24	20.02
	19.13	20.26	19.70

	NO-T	T	
NO-A	16.71	18.66	17.68
A	21.56	21.86	21.71
	19.13	20.26	19.70

MEANS, VARS, & STD ERRORS OF MEANS FOR VARIABLE DUR S1 i.e. [s] in "see"

	NORM	T	A	T-A	LB	LB-T	LB-A	LTA	MEANS
REP1 M.	13.60	16.28	16.15	18.00	14.30	15.89	18.32	18.64	16.40
V.	0.16	1.57	1.49	9.56	0.57	0.34	5.19	4.32	
S.E.	(0.164)	(0.511)	(0.499)	(1.263)	(0.308)	(0.237)	(0.930)	(0.849)	
REP2	14.17	16.02	16.41	16.15	15.38	17.04	14.49	16.15	15.73
	0.23	0.73	0.96	2.90	3.19	2.74	3.96	0.85	
	(0.198)	(0.348)	(0.401)	(0.695)	(0.729)	(0.676)	(0.812)	(0.375)	
MEANS	13.88	16.15	16.28	17.08	14.84	16.47	16.41	17.39	16.06
	0.20	1.15	1.23	6.23	1.88	1.54	4.57	2.58	
	(0.128)	(0.309)	(0.320)	(0.721)	(0.396)	(0.358)	(0.617)	(0.464)	

TWO-WAY TABLES OF MEANS

	NO-A	A	
NO-L	15.02	16.68	15.85
L	15.66	16.90	16.28
	15.34	16.79	16.06

	NO-T	T	
NO-L	15.08	16.61	15.85
L	15.62	16.93	16.28
	15.35	16.77	16.06

	NO-T	T	
NO-A	14.36	16.31	15.34
A	16.34	17.23	16.79
	15.35	16.77	16.06

MEANS, VARS, & STD ERRORS CF MEANS FOR VARIABLE DUR VSI i.e. [i] in "see"

	NORM	T	A	T-A	LB	LB-T	LB-A	LTA	MEANS
REP1 M.	8.68	10.09	11.36	12.06	10.C2	10.60	11.62	13.09	10.94
V.	1.33	1.62	2.80	1.39	0.32	1.45	3.85	2.49	
S.E.	(0.471)	(0.520)	(0.683)	(0.482)	(0.230)	(0.491)	(0.801)	(0.644)	
REP2	7.98	10.98	12.45	12.38	8.62	10.28	10.66	11.23	10.57
	0.73	1.51	2.1C	1.04	0.45	0.73	2.08	2.56	
	(0.348)	(0.501)	(0.591)	(0.416)	(0.275)	(0.348)	(0.589)	(0.653)	
MEANS	8.33	10.53	11.90	12.22	9.32	10.44	11.14	12.16	10.76
	1.03	1.56	2.45	1.22	0.39	1.09	2.97	2.53	
	(0.293)	(0.361)	(0.452)	(0.318)	(0.179)	(0.301)	(0.497)	(0.459)	

TWO-WAY TABLES CF MEANS

	NO-A	A	
NO-L	9.43	12.06	10.75
L	9.88	11.65	10.76
	9.65	11.86	10.76

	NO-T	T	
NO-L	10.12	11.38	10.75
L	10.23	11.30	10.76
	10.17	11.34	10.76

	NO-T	T	
NO-A	8.82	10.48	9.65
A	11.52	12.19	11.86
	10.17	11.34	10.76

MEANS, VARS, & STD ERRORS OF MEANS FOR VARIABLE DUR SS2 i.e. [$\int$] in "Shaw"

	NORM	T	A	T-A	LB	LB-T	LB-A	LTA	MEANS
REP1 M.	14.49	16.09	18.19	21.06	16.85	16.79	19.92	19.85	17.91
V.	0.14	1.23	5.09	11.91	1.47	1.61	10.09	9.47	
S.E.	(0.154)	(0.453)	(0.921)	(1.409)	(0.494)	(0.518)	(1.297)	(1.256)	
REP2	16.15	17.75	20.43	16.21	16.34	17.75	17.49	22.28	18.05
	0.61	1.10	6.61	8.02	0.92	2.68	7.61	19.50	
	(0.319)	(0.427)	(1.050)	(1.156)	(0.391)	(0.668)	(1.126)	(1.803)	
MEANS	15.32	16.92	19.31	18.64	16.60	17.27	18.70	21.06	17.98
	0.38	1.16	5.85	9.97	1.19	2.14	8.85	14.49	
	(0.177)	(0.311)	(0.699)	(0.911)	(0.315)	(0.423)	(0.859)	(1.099)	

TWO-WAY TABLES OF MEANS

	NO-A	A	
NO-L	16.12	18.97	17.55
L	16.93	19.88	18.41
	16.52	19.43	17.98

	NO-T	T	
NO-L	17.31	17.78	17.55
L	17.65	19.17	18.41
	17.48	18.47	17.98

	NO-T	T	
NO-A	15.96	17.09	16.52
A	19.01	19.85	19.43
	17.48	18.47	17.98

MEANS, VARS, & STD ERRORS CF MEANS FOR VARIABLE DUR VSSO   i.e. [ɔ] in "Shaw"

	NORM	T	A	T-A	LB	LB-T	LB-A	LTA	MEANS
REP1 M.	17.94	19.28	21.45	22.41	18.19	19.41	22.28	23.49	20.55
V.	0.73	1.68	3.23	2.27	0.51	3.56	2.84	5.79	
S.E.	(0.348)	(0.529)	(0.733)	(0.616)	(0.293)	(0.770)	(0.688)	(0.982)	
REP2	18.96	19.92	24.19	23.17	18.96	20.11	21.96	22.66	21.24
	0.28	0.35	2.20	4.56	1.16	1.04	1.21	2.02	
	(0.216)	(0.242)	(0.605)	(0.872)	(0.439)	(0.417)	(0.450)	(0.580)	
MEANS	18.45	19.60	22.82	22.79	18.58	19.76	22.12	23.08	20.90
	0.50	1.02	2.71	3.42	0.84	2.30	2.03	3.90	
	(0.205)	(0.291)	(0.475)	(0.534)	(0.264)	(0.438)	(0.411)	(0.570)	

TWO-WAY TABLES CF MEANS

	NO-A	A	
NO-L	19.02	22.80	20.91
L	19.17	22.60	20.88
	19.09	22.70	20.90

	NO-T	T	
NO-L	20.63	21.19	20.91
L	20.35	21.42	20.88
	20.49	21.30	20.90

	NO-T	T	
NO-A	18.51	19.68	19.09
A	22.47	22.93	22.70
	20.49	21.30	20.90

MEANS, VARS, & STD ERRORS OF MEANS FOR VARIABLE DUR S2 ie. [s] in "saw"

		NORM	T	A	T-A	LB	LB-T	LB-A	LTA	MEANS
REP1	M.	12.89	14.87	16.34	16.98	14.17	16.28	16.21	18.19	15.74
	V.	0.74	2.02	0.57	8.31	1.41	3.74	1.92	4.15	
	S.E.	(0.352)	(0.580)	(0.307)	(1.177)	(0.484)	(0.790)	(0.565)	(0.832)	
REP2		13.66	16.79	14.49	14.17	13.47	15.06	14.81	17.75	15.02
		0.33	1.49	1.37	2.05	1.32	1.62	1.98	7.55	
		(0.235)	(0.499)	(0.479)	(0.585)	(0.468)	(0.520)	(0.574)	(1.122)	
MEANS		13.28	15.83	15.42	15.58	13.82	15.67	15.51	17.97	15.38
		0.54	1.76	0.97	5.18	1.36	2.68	1.95	5.85	
		(0.212)	(0.382)	(0.284)	(0.657)	(0.337)	(0.473)	(0.403)	(0.698)	

TWO-WAY TABLES OF MEANS

	NO-A	A	
NO-L	14.55	15.50	15.02
L	14.75	16.74	15.74
	14.65	16.12	15.38

	NO-T	T	
NO-L	14.35	15.70	15.02
L	14.67	16.82	15.74
	14.51	16.26	15.38

	NO-T	T	
NO-A	13.55	15.75	14.65
A	15.46	16.77	16.12
	14.51	16.26	15.38

MEANS, VARS, & STD ERRORS CF MEANS FOR VARIABLE DUR VSO i.e. [ɔ] in "saw"

		NORM	T	A	T-A	LB	LB-T	LB-A	LTA	MEANS
REP1	M.	20.55	19.15	22.47	23.43	20.55	21.77	23.49	23.68	21.89
	V.	0.86	2.41	3.38	0.90	1.33	3.19	1.68	4.25	
	S.E.	(0.379)	(0.633)	(0.751)	(0.388)	(0.471)	(0.729)	(0.529)	(0.842)	
REP2		17.55	18.70	22.41	24.83	19.60	20.75	23.30	24.83	21.50
		1.73	9.53	2.45	0.79	4.95	3.08	1.08	3.60	
		(0.536)	(1.260)	(0.639)	(0.362)	(0.909)	(0.716)	(0.424)	(0.775)	
MEANS		19.05	18.93	22.44	24.13	20.08	21.26	23.39	24.26	21.69
		1.29	5.97	2.92	0.85	3.14	3.13	1.38	3.93	
		(0.328)	(0.705)	(0.493)	(0.266)	(0.512)	(0.511)	(0.339)	(0.572)	

TWO-WAY TABLES CF MEANS

	NO-A	A	
NO-L	18.99	23.28	21.14
L	20.67	23.83	22.25
	19.83	23.55	21.69

	NO-T	T	
NO-L	20.75	21.53	21.14
L	21.74	22.76	22.25
	21.24	22.14	21.69

	NO-T	T	
NO-A	19.56	20.09	19.83
A	22.92	24.19	23.55
	21.24	22.14	21.69

MEANS, VARS, & STD ERRORS OF MEANS FOR VARIABLE DUR I. i.e. [ɾ] in "did"

	NORM	T	A	T-A	LB	LB-T	LB-A	LTA	MEANS
REP1 M.	4.72	4.53	5.94	5.49	6.32	6.51	6.51	8.81	6.10
V.	0.68	0.79	0.63	0.22	1.16	1.64	1.11	10.44	
S.E.	(0.338)	(0.362)	(0.324)	(0.189)	(0.439)	(0.523)	(0.431)	(1.319)	
REP2	3.96	5.55	5.30	5.11	5.87	6.32	6.26	7.34	5.71
	0.45	1.10	2.78	0.39	0.45	0.92	0.86	3.31	
	(0.274)	(0.428)	(0.681)	(0.255)	(0.274)	(0.392)	(0.379)	(0.743)	
MEANS	4.34	5.04	5.62	5.30	6.10	6.42	6.38	8.07	5.91
	0.57	0.94	1.71	0.30	0.80	1.28	0.99	6.88	
	(0.217)	(0.280)	(0.377)	(0.159)	(0.259)	(0.327)	(0.287)	(0.757)	

TWO-WAY TABLES OF MEANS

	NO-A	A	
NO-L	4.69	5.46	5.07
L	6.26	7.23	6.74
	5.47	6.34	5.91

	NO-T	T	
NO-L	4.98	5.17	5.07
L	6.24	7.25	6.74
	5.61	6.21	5.91

	NO-T	T	
NO-A	5.22	5.73	5.47
A	6.00	6.69	6.34
	5.61	6.21	5.91

MEANS, VARS, & STD ERRORS CF MEANS FOR VARIABLE TOTAL DUR. of sentence. (Note all measurements here in deciseconds)

		NORM	T	A	T-A	LB	LB-T	LB-A	LTA	MEANS
REP1	M.	16.36	17.82	20.58	21.63	17.85	19.20	21.86	22.51	19.73
	V.	0.66	0.39	2.75	1.18	0.08	2.25	1.05	1.93	
	S.E	(0.331)	(0.256)	(0.678)	(0.443)	(0.117)	(0.612)	(0.418)	(0.568)	
REP2		16.86	18.44	21.23	21.27	17.82	19.52	20.04	21.23	19.55
		0.26	0.22	0.63	0.76	0.71	0.80	1.26	0.72	
		(0.208)	(0.191)	(0.324)	(0.356)	(0.345)	(0.366)	(0.459)	(0.346)	
MEANS		16.61	18.13	20.91	21.45	17.84	19.36	20.95	21.87	19.64
		0.46	0.30	1.69	0.97	0.40	1.53	1.16	1.33	
		(0.195)	(0.159)	(0.376)	(0.284)	(0.182)	(0.357)	(0.311)	(0.332)	

TWO-WAY TABLES CF MEANS

	NO-A	A	
NO-L	17.37	21.18	19.27
L	18.60	21.41	20.00
	17.99	21.29	19.64

	NO-T	T	
NO-L	18.76	19.79	19.27
L	19.39	20.61	20.00
	19.08	20.20	19.64

	NC-T	T	
NO-A	17.22	18.75	17.99
A	20.93	21.66	21.29
	19.08	20.20	19.64

APPENDIX 2

SOME RESULTS OF THE SIGNAL DETECTION TASK DESCRIBED IN CHAPTER 6, SECTION 3.5.3.

The tables show the subject's response (marked ✓) for each detection trial under the Topical Anaesthetic, Auditory Masking and Topical Anaesthetic plus Auditory Masking conditions. Trials containing the signal are shown as 1; catch trials (i.e. those containing no signal) are shown as 0. For each experimental condition, there were 100 "signal present" and 100 "signal absent" trials. The force-stimuli used were 0 gm. for the Ausitory Masking condition, and .75 gm. for both the Topical Anaesthetic and the Topical Anaesthetic plus Auditory Masking conditions.

Auditory Masking Condition

Signal	Response Category				Signal	Response Category				Signal	Response Category				Signal	Response Category			
	1	2	3	4		1	2	3	4		1	2	3	4		1	2	3	4
1				✓	1				✓	0	✓				1				✓
1				✓	0	✓				0	✓				1				✓
1				✓	1				✓	1			✓		1				✓
1				✓	1				✓	1				✓	1				✓
0	✓				1				✓	1				✓	0	✓			
1				✓	1				✓	1				✓	1			✓	
1				✓	1				✓	1				✓	1				✓
0	✓				0	✓				0	✓				0	✓			
0	✓				0	✓				0	✓				0	✓			
0	✓				0	✓				1			✓		0	✓			
0	✓				1				✓	1				✓	0	✓			
1				✓	0	✓				0	✓				1				✓
1				✓	1				✓	0	✓				1				✓
1				✓	1				✓	0	✓				1				✓
0	✓				0	✓				0	✓				0	✓			
0	✓				0	✓				0	✓				0	✓			
1				✓	0	✓				0	✓				1				✓
1				✓	0	✓				0	✓				1				✓
0	✓				0	✓				0	✓				0	✓			
0	✓				0	✓				1				✓	0	✓			
1				✓	0	✓				1				✓	1				✓
1				✓	0	✓				1				✓	1				✓
0	✓				1				✓	1				✓	0	✓			
1				✓	1			✓		1				✓	1				✓
0	✓				1				✓	1				✓	0	✓			
1				✓	1				✓	0	✓				1				✓
1				✓	1				✓	0	✓				1				✓
0	✓				1				✓	1			✓		0	✓			
0	✓				0	✓				0	✓				0	✓			
0	✓				0	✓				0	✓				0	✓			
1			✓		0	✓				1				✓	1			✓	
0	✓				0	✓				0	✓				0	✓			
0	✓				1			✓		1				✓	0	✓			
0	✓				1				✓	0	✓				0	✓			
0	✓				1				✓	0	✓				0	✓			
1				✓	0	✓				0	✓				0	✓			
1				✓	0	✓				0	✓				1				✓
1				✓	0	✓				0	✓				1				✓
1				✓	0	✓				1				✓	1			✓	
0	✓				0	✓				0	✓				1				✓
0	✓				1				✓	1				✓	0	✓			
0	✓				0	✓				1				✓	0	✓			
0	✓				1				✓	0	✓				0	✓			
0	✓				0	✓				1				✓	0	✓			
0	✓				0	✓				1				✓	0	✓			
0	✓				1				✓	1				✓	1				✓
1				✓	1			✓		1				✓	1				✓
1				✓	1				✓	1				✓	1				✓
1				✓	1				✓	1				✓	1				✓
1				✓	1				✓	0	✓				0	✓			

Topical Anaesthetic Condition

Signal	Response Category				Signal	Response Category				Signal	Response Category				Signal	Response Category			
	1	2	3	4		1	2	3	4		1	2	3	4		1	2	3	4
1				✓	0	✓				1				✓	1		✓		
1				✓	1				✓	1		✓			0	✓			
1				✓	1				✓	1				✓	0	✓			
1				✓	1				✓	1			✓		0	✓			
0	✓				0	✓				1				✓	0	✓			
1			✓		0		✓			0	✓				1				✓
1			✓		1			✓		1			✓		1				✓
0		✓			1			✓		1		✓			0	✓			
0	✓				0	✓				0	✓				0	✓			
0	✓				0	✓				0	✓				0	✓			
0	✓				0	✓				0	✓				1			✓	
1				✓	0	✓				0	✓				0	✓			
1			✓		1				✓	1	✓				0	✓			
1		✓			0	✓				1			✓		0	✓			
0	✓				1		✓			1		✓			0	✓			
0	✓				1			✓		0	✓				1				✓
1				✓	1		✓			1				✓	1			✓	
1			✓		0	✓				1				✓	1				✓
0	✓				0	✓				0	✓				0	✓			
0		✓			0	✓				1				✓	1				✓
1				✓	0	✓				0	✓				0	✓			
1				✓	1		✓			0	✓				0	✓			
0	✓				1		✓			0	✓				0	✓			
1	✓				0	✓				1				✓	0	✓			
0	✓				1			✓		0	✓				0	✓			
1	✓				0	✓				1			✓		1			✓	
1		✓			0		✓			0		✓			1				✓
0	✓				0	✓				1			✓		1				✓
0	✓				0	✓				1				✓	1				✓
0	✓				1				✓	1				✓	1			✓	
1			✓		1				✓	0	✓				1		✓		
0	✓				0		✓			0	✓				1			✓	
0		✓			0	✓				1			✓		1				✓
0	✓				0	✓				1				✓	0	✓			
0	✓				1				✓	0	✓				1		✓		
1		✓			0	✓				0		✓			1				✓
1				✓	0	✓				0	✓				1				✓
1			✓		0	✓				0	✓				1				✓
0		✓			0		✓			0	✓				1				✓
1			✓		1				✓	0	✓				1			✓	
1				✓	1				✓	1				✓	1		✓		
1			✓		1				✓	0	✓				1				✓
0	✓				0	✓				1		✓			1				✓
1				✓	1			✓		1				✓	1	✓			
0	✓				0	✓				1			✓						
1			✓		0	✓				0	✓								
0	✓				0	✓				0	✓								
0	✓				0	✓				0	✓								
0	✓				0	✓				0	✓								
1				✓	0	✓				1				✓					
0	✓				1		✓			1			✓						
1				✓	1			✓		0	✓								

Topical Anaesthetic Plus Auditory Masking Condition

Signal	Response Category 1	2	3	4	Signal	Response Category 1	2	3	4	Signal	Response Category 1	2	3	4	Signal	Response Category 1	2	3	4
1				✓	0	✓				0	✓				1				✓
1		✓			0	✓				0	✓				0	✓			
1			✓		0		✓			0	✓				1			✓	
1				✓	1			✓		1				✓	0	✓			
0	✓				0	✓				1			✓		1				✓
0	✓				1				✓	0	✓				1				✓
0		✓			1				✓	1				✓	1				✓
0	✓				0	✓				0	✓				1				✓
0	✓				0	✓				1		✓			0	✓			
0	✓				0	✓				1				✓	1			✓	
1			✓		0	✓				0		✓			0		✓		
0	✓				1			✓		0	✓				0	✓			
1				✓	1				✓	1				✓	0	✓			
1			✓		1			✓		1				✓	1				✓
1			✓		0	✓				0	✓				1		✓		
0	✓				1				✓	0	✓				0	✓			
0	✓				0	✓				1				✓	1				✓
0		✓			0	✓				1				✓	0	✓			
0	✓				0	✓				1			✓		1				✓
1				✓	0	✓				0	✓				0	✓			
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GLOSSARY OF SOME TECHNICAL TERMS USED

(sources : Cunningham, 1964 : Zemlin, 1964 Kaplan, 1960)

Action potential : Electrical energy generated by nerve or muscle activity.

Afferent nerves : Conducting towards the central nervous system. The opposite of efferent. Also called sensory nerves.

Antagonist muscles : Muscles which relax to enable the protagonist muscles to operate and which are capable, by contraction, of opposing the movement.

Cartilage : A nonvascular connective tissue, softer and more flexible than bone.

Condyle : A knuckle. A smooth rounded eminence covered with articular cartilage e.g. condyle of mandible.

Cornu : A horn e.g. cornu of hyoid bone.

Coronal : A vertical plane, or cut from side to side, dividing the structure into front and back parts.

Cutaneous : Pertaining to the skin.

Decussate : To cross over, as nerves or muscle fibres e.g. as in the intrinsic muscles of the tongue.

Efferent : Conducting from a central region to the periphery e.g. motor nerves supplying muscles of the tongue.

EMG : Electromyography. A technique for recording the electrical energy generated by active muscles.

End-organ : A terminal structure of a nerve, also called sensory receptor.

EPG : Electropalatography. A technique for recording the changing patterns of tongue contacts with the palate.

Exteroceptors : Sensory receptors situated on the surface of the body conveying to the CNS information concerning the environment. They include tactile and taste receptors.

Feedback : A term borrowed from radio technicians to mean the diversion of a small part of the output to control the input. It occurs both in natural and man-made systems.

Fixator muscles : Muscles which provide a fixed, stable base from which other muscles can contract.

Foramen : An opening or perforation in a bone, e.g. mandibular foramen.

Innervation : The supplying of any organ with nerve fibres.

Insertion : The area of attachment of a muscle to the structure it moves.

Interdigitate : The interlocking of similar parts, as muscle fibres from different muscles.

Ion : An atom or group of atoms which, due to outside force, has lost or gained one or more orbital electrons and thus becomes capable of conducting electricity.

Kinesthetic : A general term referring to the sense of movement and/or position of parts of the body. Kinesthetic sensation probably results from an integration in the CNS of information supplied by tactile and proprioceptive receptors.

Lamina : A plate or sheet. Hence lamina propria : sheets of tissue.

Ligament : A band of flexible elastic dense fibrous connecting tissue, connecting the articular ends of bones. Sometimes found in a capsule, completely enveloping the joint.

Maxilla : The right or left upper jaw.

Myelinated nerve fibres : Nerve fibres surrounded by fatty sheaths formed by Schwann cells.

Origin : The place of attachment of a muscle which remains fixed during contraction.

Papilla : A small nipple-like eminence. Pl. papillae, e.g. papillae of the tongue.

Plexus : A network of nerves or veins.

Proprioceptive : Pertaining to information supplied to the CNS (probably the cerebellum) from the muscle spindles, joint receptors and Golgi tendon organs.

Protagonist (or prime mover) muscles : Muscles effecting the actual movement which occurs.

Raphe : A line of union between the members of a bilaterally symmetrical structure.

Reflex : An involuntary, relatively invariable adaptive response to a stimulus, e.g. stretch reflex.

Sagittal : Pertaining to the anteroposterior median plane of the body.

Septum : A partition, e.g. a fibrous septum separating two groups of muscle fibres.

Servo-system : An automatic mechanism in which the output is partly controlled by feeding back a part of the output to the controlling elements.

Skeletal muscle : Muscle which executes movements initiated by the will. Also known as voluntary and striated muscle.

Striated muscle : Voluntary muscle so-called because it shows under a microscope characteristic transverse striation alternately pale and dark.

Symphysis : The point of union between bones that were originally separate, e.g. mandibular symphysis.

Synapse : The region where two neurones meet and where impulses are passed from one to the other.

Synergistic muscles : Muscles which assist the protagonist muscles in effecting a particular movement.

Tendon : A non-elastic band of connective tissue that forms the attachment of muscle to bone.

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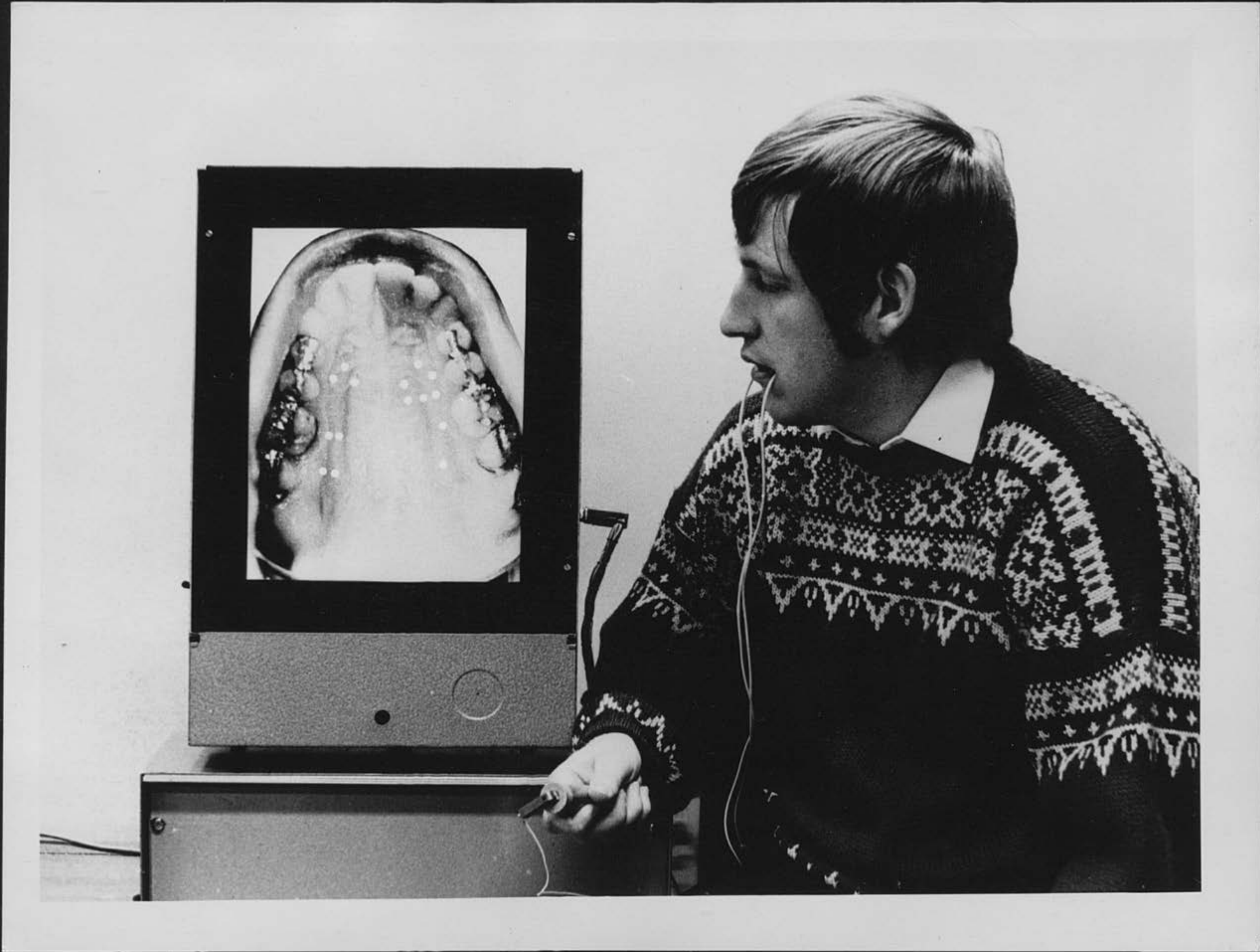
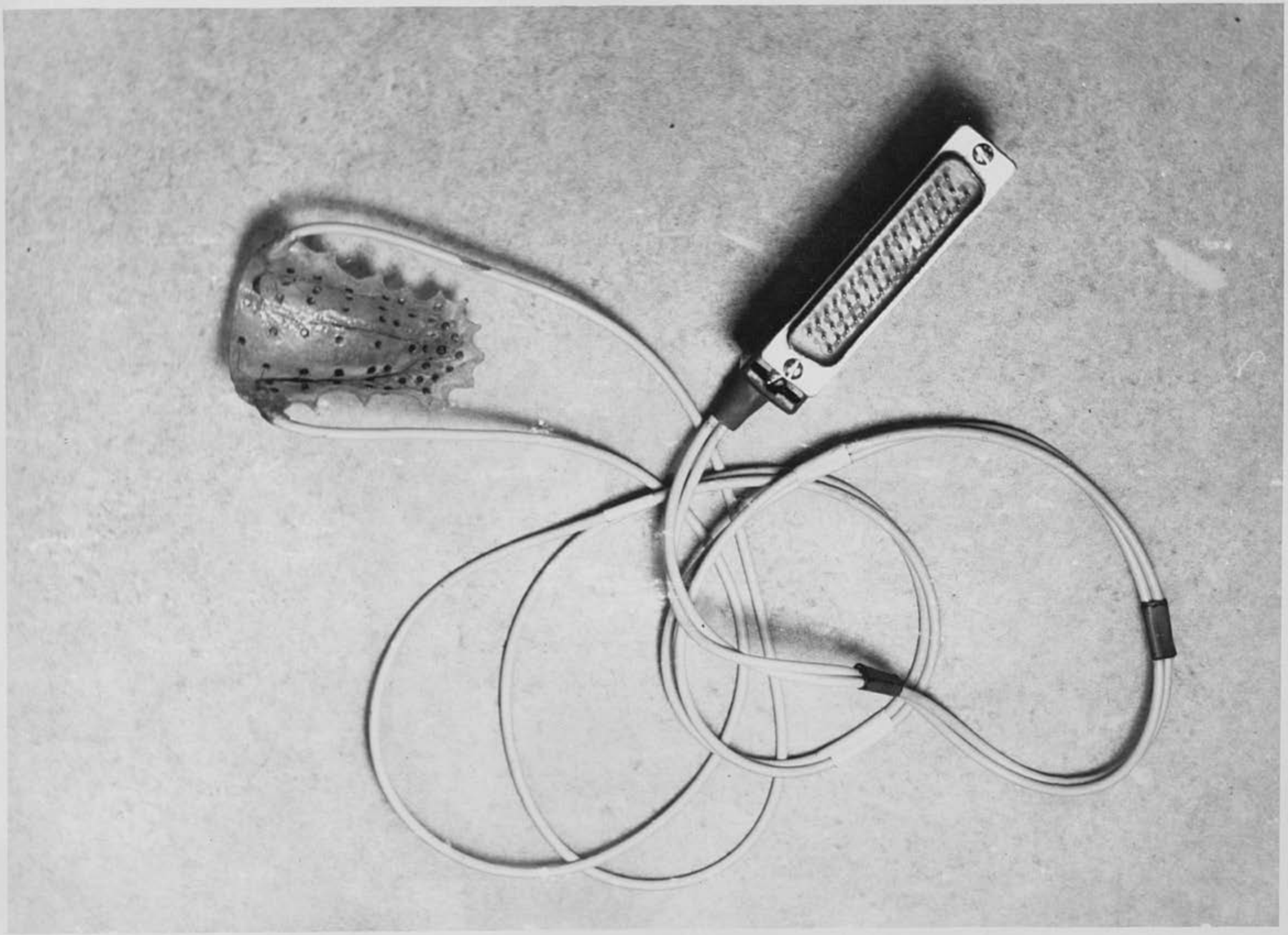
Photograph No. 1.

View of the subject operating the Prototype 1 electropalatograph.



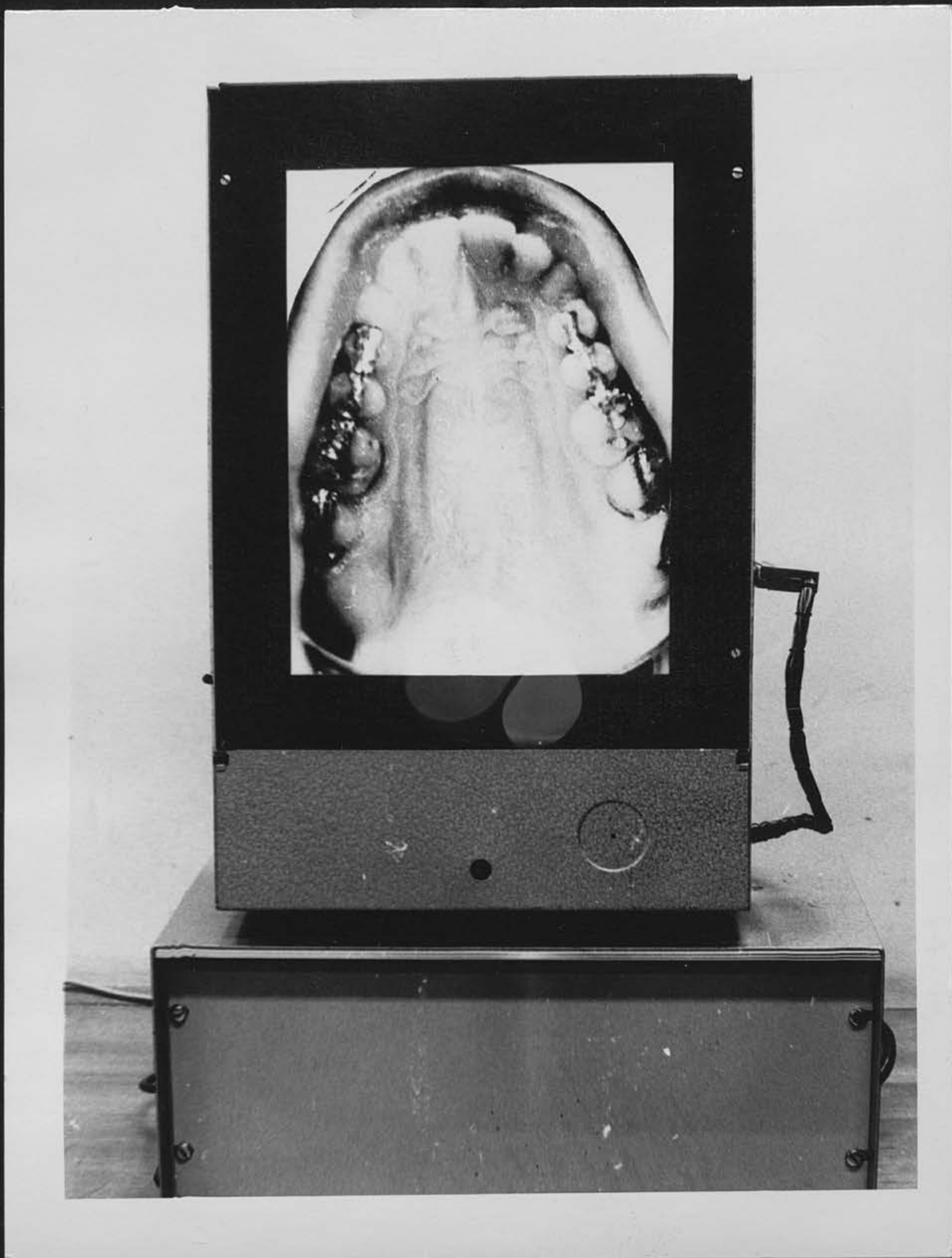
Photograph No. 2.

The artificial palate used in the
Prototype 1 electropalatograph.



Photograph No. 3.

The display unit of the electropalatograph, showing the enlarged photograph of the subjects palate.



Photograph No. 4.

The experimental lay-out for the investigation described in Chapter 6. The subject using the electropalatograph is seated out of sight to the right of the display unit.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Photograph No. 5.

The Edinburgh oral aesthesiometer in operation.